N71-29011

NASA TECHNICAL MEMORANDUM

NASA TM X-67865

NASA TM X-67865

CASE FILE COPY

OPTIMIZATION OF ENGINES FOR A MACH 0.98 TRANSPORT WITH LOW TAKEOFF AND APPROACH NOISE LEVELS

by Gerald A. Kraft and John B. Whitlow, Jr.
Lewis Research Center
Cleveland, Ohio
June, 1971

This information is being published in preliminary form in order to expedite its early release.

E-6407

ABSTRACT

A parametric engine study was made for a Mach 0.98 advanced technology transport using the supercritical wing. A 1978 year of first flight was assumed for the 300-passenger airplane which had a takeoff gross weight of 386 000 pounds.

The engine that gave the greatest range generated too much noise. When noise constraints were used, the best fan pressure ratio was as high as duct jet noise would allow. A noise goal of 106 PNdB could be met with a 500-nautical-mile range penalty using 7 PNdB machinery noise suppression. A noise goal of 86 PNdB could be met at a range penalty of 650 miles if 40 PNdB of machinery noise suppression is available. This penalty could be reduced if a light-weight jet noise supporessor was used.

E-6407

OPTIMIZATION OF ENGINES FOR A MACH 0.98 TRANSPORT WITH LOW TAKEOFF AND APPROACH NOISE LEVELS

by Gerald A. Kraft and John B. Whitlow, Jr.

Lewis Research Center

SUMMARY

A parametric turbofan engine study was made for a Mach 0.98 advanced technology transport using the Whitcomb supercritical wing. Engine weight and turbine cooling technology compatible with a 1978 year of first flight were used for the three-engine airplane. Takeoff gross weight was fixed at 386 000 pounds which provided a range exceeding 3000 nautical-miles for the 300-passenger plane.

Design point engine calculations were made at cruise. Some approximations based on off-design matching calculations were made to determine the takeoff operating conditions. Approach conditions were computed with an off-design matching computer program. Differences in climb and letdown fuel of the various engines of this study were ignored. Fan pressure ratio was varied from 1.7 to 3.0 and turbine-rotor-inlet-temperature was varied from 2300° to 3000° F at the takeoff condition. Turbomachinery noise suppression was assumed to vary from 0 to 40 PNdB, as necessary, even though only 15 PNdB has been demonstrated to date. A jet noise suppressor capable of 10 PNdB suppression was assumed under some conditions to determine its usefulness. The jet suppressor was assumed to be weightless, but the turbomachinery noise suppression was not.

With noise constraints, the best fan pressure ratio was as high as duct jet noise would allow at any noise goal. A noise goal of 106 PNdB could be met with a range penalty of 500 miles using only 7 PNdB machinery noise suppression. A noise goal of 86 PNdB could be met using

40 PNdB of machinery noise suppression for a range penalty of 650 miles. This penalty could be reduced to as low as 300 miles if weightless jet noise suppressors were assumed also. It was found that increasing turbine-rotor-inlet temperature from 2300° to 3000° F did not improve the range measurably for any noise goal between 106 and 86 PNdB. It was also found that the inlet, duct, duct nozzle, and engine weight were likely to cause large changes in range if not designed for minimum losses.

INTRODUCTION

The supercritical wing proposed by Whitcomb (ref. 1) offers the potential for delaying the transonic drag rise experienced by present-day subsonic jet transports as their flight speed approaches Mach 1.0. Transport airplanes using this wing could then cruise at somewhat higher speeds than those in present commercial use with little or no penalty in lift-drag ratio, L/D. Reference 2 was an engine optimization study for the same airplane used in this study. However, reference 2 reported the optimum cycle parameters for a noise goal of 106 PNdB only when a limit of 15 PNdB machinery noise suppression was assumed. The main purpose of this report was to determine the optimum engine parameters for noise goals from 106 to 86 PNdB. In order to accomplish this, turbomachinery noise suppression was varied from 0 to 40 PNdB as needed even though only about 15 PNdB of suppression has been demonstrated to date by acoustically treating inlets and ducts. In addition to this, the benefits of a weightless, 10 PNdB jet noise suppressor were investigated. The secondary purpose of this report was to determine how sensitive the range is to the choice of design component efficiencies, pressure losses, thrust coefficients, and engine weight.

Present day airframe weights and engine component efficiencies were used in this study along with engine weights representative of an engine designed for a first flight in the year of 1978. The cruise speed selected was Mach 0.98 and the airplane was sized to carry 300 passengers at least 3000 nautical miles. Takeoff gross weight (TOGW) was fixed throughout the study at 386 000 pounds and operating empty weight without engines was fixed at 180 000 pounds.

Only a three-engine configuration was studied. Bypass ratio (BPR) and overall pressure ratio (OPR) were optimized for maximum range at each value of fan pressure ratio (FPR). The FPR was varied from 1.7 to 3.0 at a sea-level-static turbine rotor-inlet-temperature (T_4) of 2300° F. This T_4 was chosen based on the results of reference 2 which indicated no important advantage in striving for high values of T_4. The engine drag was allowed to vary as a function of engine diameter in this report. In reference 2, the engine drag was assumed to be constant. Since high T_4's usually mean small engines, it was felt that high T_4's might look somewhat better in this report than in reference 2. Therefore, in a separate section of the report, T_4 was varied from 2300° to 3000° F while FPR was held at 1.70. The FPR was held at this value so that the lowest noise goal considered in this paper, 86 PNdB, could be examined across the entire T_4 range.

There were some differences between this report and reference 2 in the values assumed for component efficiencies and cycle pressure losses. To find out what these differences might mean to the optimum cycle parameters reported in reference 2 for a noise goal of 106 PNdB, the optimization of reference 2 was repeated at the end of this study. The engine drag was assumed constant, FPR was fixed at 1.70, and T_4 was held at 2300° F. Only the 106 PNdB noise goal was considered.

SYMBOLS

BPR	bypass ratio
C_s	speed of sound, knots (naut. mi/hr)
C_L	lift coefficient
D	drag, lb

F_N	net thrust, lb
FPR	fan pressure ratio
L	lift, lb
M	Mach number
OEW	operating empty weight, lb
OPR	overall compressor pressure ratio
P	total pressure, lb/ft^2
R	range, naut. mi.
sfc	specific fuel consumption, (lb fuel/hr)/lb thrust
Swing	wing reference area, ft^2
T	total temperature, ^oR
TOGW	takeoff gross weight, lb
W_A	total engine airflow, lb/sec
$W_{end\ cr}$	airplane gross weight at the end of cruise, lb
W_{eng}	installed weight of 3 engines, lb
W_G	takeoff gross weight, lb
$W_{start\ cr}$	airplane gross weight at the start of cruise, lb
β	turbine cooling bleed, chargeable to cycle, percent of core airflow
δ	pressure parameter, P/2116
θ	temperature parameter, T/519

Subscripts

cr	cruise
ref	reference
s.l.s.	sea-level-static
T.O.	takeoff

1	fan face station
4	turbine-rotor-inlet station

METHOD OF ANALYSIS

Selection of Takeoff Gross Weight and Airframe Weight

It was desired to select a takeoff gross weight (TOGW) that gives a range of about 3000 nautical miles for a wide-body airplane which is designed to carry 300 passengers.

Figure 1 shows how the operating empty weight (OEW) varies with TOGW for turbofan-powered subsonic transports either now flying or soon to be flying. Data points shown were obtained from reference 3. It was assumed that the airplane of this study could be located on this weight curve. An iterative procedure was used to determine the TOGW of this study airplane.

To begin the iteration, a TOGW was arbitrarily assumed. The OEW was then found from figure 1. The payload of 60 000 pounds (300 passengers at 200 lb each) was then added to the OEW. The total fuel load was obtained by subtracting this sum from the TOGW that was assumed. The mission fuel was assumed to be 82 percent of the total fuel thus calculated. (18 percent of the total fuel load is held in reserve.) 20 000 pounds of fuel was assumed to be used during climb up to cruise. The airplane weight at the start of cruise, then, was the TOGW minus 20 000 pounds. The weight at the end of cruise was the difference between the TOGW and the mission fuel with the letdown fuel added back in. The letdown fuel was assumed to be 2000 pounds. These weights at the beginning and end of cruise were then substituted into the Brequet range equation.

Present-day subsonic jet transports have cruise L/D ratios (excluding engines) in the order of 20.0. In the absence of experimental data, it was assumed for this study that the cruise L/D of a transonic (Mach 0.98 airplane employing a supercritical wing is 18.5. A small error in the assumed L/D would not change the optimization study which was done in this report. Additional drag due to the engines was also indicated, as discussed in the section on engines. An sfc of 0.70/hour (representative of installed sfc for a high-bypass-ratio engine) was used in the iteration. Total range was obtained by adding climb and letdown range to the cruise range obtained from the Breguet equation.

The preceding calculation was repeated, as necessary, assuming a new value of TOGW until a total range of 3000 nautical miles was obtained. After several iterations it was found that a TOGW of 386 000 pounds and an OEW of 220 000 pounds satisfied this condition. TOGW was fixed at 386 000 pounds for the remainder of the study.

Three podded engines of existing weight technology were found to weigh about 40 000 pounds total (installed) when sized for 120 000 pounds sea-level-static thrust. By subtracting the weight of three of these engines from the OEW of 220 000 pounds, it was found that the airframe would weigh 180 000 pounds. The airframe weight was then fixed at this value for the rest of the study. Total fuel weight and, hence, range vary in this study as engine weight changes. The weight breakdown is summarized below for the reference airplane which resulted from the basic iteration descrived. Those items which remained fixed for the rest of the study are noted as "(fixed.)"

Airframe weight, lb (fixed)	180 000
Engine weight, lb (bare engine weight + $3.13 \times Wa_{sls} \sqrt{\theta_1}/\delta_1$) . .	40 000
Payload, lb (fixed)	60 000
Climb fuel, lb (fixed)	20 000
Cruise fuel, lb	64 920
Descent fuel, lb (fixed)	2 000
Reserve fuel, lb (0.18 × total fuel)	19 080
TOGW, lb (fixed)	386 000

A sketch of the airplane used in this study is shown in figure 2. The engines are mounted in the rear of the aircraft to provide a clean wing in order to achieve a high L/D at cruise.

Calculation of Airplane Range

The sum of total fuel weight and installed engine weight was constant in this study since TOGW, payload, and airframe weight were constant. As engine weight changed, therefore, total fuel weight also changed. Total fuel weight is one of the most important variables in this study where range is used as the figure of merit. The other major factors are cruise sfc and cruise L/D. Cruise range was calculated from the Breguet range equation which can be expressed as

$$R_{cr} = 561 \frac{L/D}{sfc} \ln \frac{\text{Weight at start of cruise}}{\text{Weight at end of cruise}} \tag{1}$$

when

$$M = 0.98$$

$$C_s = 573 \text{ knots (n. mi/hr)}$$

The airplane weight at the start of cruise is simply the TOGW minus climb fuel. Climb fuel was assumed constant at 20 000 pounds for this entire study. The airplane weight at the end of cruise was obtained by subtracting the mission fuel from the TOGW and adding back the letdown fuel. The letdown fuel was assumed to be 2000 pounds for this entire study. The mission fuel is equal to the sum of the climb, cruise, and letdown fuel. It is also equal to 82 percent of the total fuel load. The reserves were always 18 percent of the total fuel. Thus equation (1) can be rewritten as

$$R_{cr} = 561 \frac{L/D}{sfc} \ln \frac{366\ 000}{268\ 000 + 0.82\ W_{eng}}$$

The total range was assumed to be 350 nautical miles greater than the cruise range for all cases. This was composed of a 200-mile climb and a 150-mile letdown.

Engines

The long-duct, separate-flow (unmixed) exhaust turbofan engines of this study were sized for cruise. A sketch of a typical engine pod is shown in figure 3. Sound-deadening material is shown in the duct walls and splitter and in the inlet walls and centerbody surface. In addition, an inlet ring concentric with the centerbody and outer wall is shown with sound deadening material. For any given amount of suppression a detailed analysis is necessary to determine the correct number of inlet rings and duct splitters.

Engine design point cycle calculations were made at cruise for a range of engines with FPR of 1.70 to 3.00 at a $T_{4,cr}$ of 2100° F. BPR and OPR were optimized at each FPR for maximum range. In addition, three levels of cruise T_4 were considered at an FPR of 1.70. They were 2100°, 2450°, and 2800° F. Cycle calculations were also made at the sea-level-static, the 152-knot-liftoff, and the 135-knot-approach conditions. Takeoff and liftoff T_4's were always assumed to be 200° F higher than cruise T_4. At off-design conditions a modified version of the computer matching program of reference 4 was used to determine the engine component efficiencies, pressure ratios, and airflows. These were based on component maps typical of high BPR engines.

At the engine design point, the design parameters were held fixed as follows for all the study engines:

Fan adiabatic efficiency	0.88
Compressor adiabatic efficiency	0.89
Combustor efficiency	0.99
Inner turbine adiabatic efficiency	0.91
Outer turbine adiabatic efficiency	0.90
Inlet pressure recovery	0.98
Pressure ratio across combustor	0.96
Total duct pressure ratio from fan discharge to nozzle	0.94
Total core pressure ratio from low pressure turbine discharge to nozzle	0.98
Exhaust nozzle thrust coefficient (both streams)	0.98

When T_4 was varied, the chargeable turbine cooling bleed was estimated to vary with T_4 as shown in figure 4. Chargeable cooling bleed is the total cooling bleed minus the high pressure turbine stator bleed. The sketch at the top of the figure shows where the bleed is added back into the main stream in the cycle analysis. This schedule of cooling bleed assumes that at a $T_{4,sls}$ of 2300° F all stators and rotors are convection cooled. At a $T_{4,sls}$ of 2750° F, the stator and rotor of the high pressure turbine are film cooled (full coverage). At a $T_{4,sls}$ of 3000° F, only the rotor of the low pressure turbine is convection cooled. The rest of the turbine is film cooled. The slope of the bleed schedule (fig. 4) is based on the cooling technology estimated to be available in 1978 (unpublished data by F. S. Stepka of Lewis Research Center).

Uninstalled engine weight was allowed to vary with the sea-level-static BPR, OPR, T_4, and total airflow as described by Gerend and Roundhill (ref. 5). They have also correlated engine weight with the year of first flight. It was assumed that the engines of this study would first fly in 1978. The additional weight for installation (including inlet, nacelle, and nozzle) was assumed to be 3.13 times the total airflow at takeoff. This installation weight is based on empirical data for existing high-bypass-ratio engines used in large commercial transports.

The engine diameters and lengths were also computed by the method of reference 5. A preliminary estimate of nacelle drag as a function of diameter is given in figure 5(a). This schedule of drag has a slope which is indicative of nacelle skin friction. Skin friction drag is usually proportional to maximum diameter raised to some power just under two. Since skin friction drag cannot be avoided, this schedule of drag rise with diameter should be the minimum encountered. Other drag increases with diameter can possibly be ignored by proper design, installation, and use of favorable interference. This schedule is representative of the schedules being used by engine and airframe contractors in industry. The use of this schedule causes the L/D of the airplane to change as engine diameter changes. This is shown in figure 5(b). For the iterative process used to establish the reference TOGW, the engine diameter was assumed to be 80 inches. Using the drag from figure 5(a) at 80 inches and the L/D of the airplane without engines (as previously mentioned) leads to a reference L/D of about 16.8 when engines are included. In this study, then, engines with diameters greater than 80 inches caused L/D to be less than 16.8 and engines with less than 80-inch diameters caused L/D to be greater than 16.8. This is in contrast to reference 2, where the L/D was fixed at the reference value regardless of engine diameter.

Noise Constraints and Calculations

Noise calculations were made for two measuring points, both of which are specified in Federal Air Regulation Part 36. They were:

(1) Sideline noise measured immediately after lift-off on a 0.25-nautical-mile (1520-ft) sideline on the ground at the angle of maximum noise.

(2) Approach noise, when the airplane is 1 nautical mile from the runway threshold, measured on the ground directly under the glide path at the angle of maximum noise. The airplanes of this study were assumed to be at an altitude of 370 feet at this measuring station (i.e., a 3° glide slope).

For an airplane having a TOGW of 386 000 pounds, F.A.R. Part 36 specifies a noise limit of 106.5 EPNdB for both of the above measurements. A third measurement specified by this regulation should be made at a point 3.5 nautical miles after the start of takeoff roll on the extended runway centerline. If the altitude exceeds 1000 feet, the thrust may be reduced to that required for a 4 percent climb gradient or to maintain level flight with one engine out, whichever thrust is greater. The noise limit at this measuring station for the airplane weight considered here is 104 EPNdB. This noise measurement was ignored in this study because it was felt that with the high BPR engines considered herein it would be possible to gain altitude quickly after takeoff. (High BPR engines (BPR $\geq$ 2), sized for the cruise condition in this report, generally have takeoff thrust-to-gross-weight ratios F_N/W_G superior to existing low BPR, turbofan-powered transports.) The higher altitude should provide considerable noise attenuation. Also, the high thrust level available at takeoff should permit a considerable reduction in thrust at the 3.5-mile point where the climb gradient is reduced. The reduction in thrust will reduce the level of noise generated at any given altitude.

Total perceived noise has two components - jet noise from the two jet streams and fan turbomachinery noise. Jet noise, measured in PNdB, was calculated by standard methods described by the Society of Automotive Engineers in references 6 and 7. Jet noise is primarily dependent on the exit velocities of the two flow streams, but is also affected by the gas flow rates and the flow areas. These variables were calculated at both Mach 0.23 (152 knots) after lift-off at full thrust and with thrust cut back to 12 000 pounds per engine during approach at Mach 0.203 (135 knots). At relative jet velocities below 1000 feet per second, there is some uncertainty about how overall sound pressure level (OASPL) varies. In this report, the semi-log plot of the curve of OASPL against relative jet velocity shown in figure 1 of reference 6 was extrapolated as a straight line below 1000 feet per second. While this technique is not used exclusively throughout the industry, it does agree with recent data published in reference 8.

Fan turbomachinery noise, also measured in PNdB, is a function of many things - for example, spacing between stator and rotor, tip speed, number of stages, fan pressure ratio, thrust, and amount of nacelle acoustic treatment. In this study, it was assumed that the engines would be built with optimum stator-rotor spacing and without any inlet guide vanes in order to minimize noise. Curves developed by the Propulsion Systems Acoustic Branch at NASA-Lewis, and presented in reference 8, relate fan machinery noise to FPR for both one- and two-stage fans. These noise curves were scaled from a net thrust of 90 000 pounds and a measuring-point distance of 1000 feet to both the approach and sideline conditions of this report. In addition to logarithmic thrust and distance-squared scaling, extra air absorption due to a change in slant range (ref. 6) was included. The curves which result for both the approach and the takeoff sideline conditions are shown in figure 6. Since the turbomachinery noise is a function of thrust, figure 6(b) is valid only for a range of $\left(F_N/W_G\right)_{sls}$ from 0.23 to 0.37. This represents an $F_{N,sls}$ of from 89 200 to 143 500 pounds, which covers the range of interest in this report. Over this range of $F_{N,sls}$ the noise shown in figure 6(b) would vary only ±1 PNdB. Total noise at both takeoff and approach conditions was obtained by adding anti-logarithmically the machinery and jet perceived noise, as described in reference 6.

The noise calculations made in this study are in units of PNdB. The F.A.R. Part 36 requirements, however, are stated in terms of EPNdB. The EPNdB scale (where E stands for effective) is a modification of the PNdB scale where a correction is made to account for (1) subjective response to the maximum pure tone and (2) the duration of the noise (ref. 9) heard by the observer. These modifications to the PNdB scale were ignored in this study, since the amount of information known about the maximum tones and directivity of the noise from these parametric engines is rather limited. It is thought that the error introduced by ignoring these modifications is less than the error that might occur by making further assumptions about the noise sources.

Fan machinery noise can be attenuated by acoustically treating the inlets and ducts. According to reference 8, acoustic treatment can reduce this noise as much as 15 PNdB. The ducts of the turbofan engines of this study are long (see fig. 3), so they readily lend themselves to wall treatment with a porous sound-absorbing sandwich material such as that described in reference 10. Duct and inlet wall treatment and an acoustically lined splitter ring inserted in the inlet were found in reference 11 to penalize the weight of a Pratt & Whitney JT3D engine about 370 pounds. Much of this weight penalty is undoubtedly tied up in structural modifications since the lining material by itself is very light. This amount of treatment on the JT3D engines of a DC8 airplane lowered the approach noise about 11 PNdB. The addition of one splitter to the inlet of some of the high BPR engines of this study may not be as effective in reducing approach noise of these engines as it was for the low-BPR JT3D because of the larger inlet diameter-to-sound-wave length ratio (ref. 12). If a single splitter ring is placed in the inlet, it is estimated that it will be most effective if placed about 8 inches from the wall. It was estimated in this study that this type of inlet and duct treatment combined will reduce the fan machinery noise about 10 PNdB. The full 15 PNdB reduction, which is the maximum demonstrated to date, could be attained only by the addition of more splitter rings in the inlet and probably the addition of a splitter ring or radial splitters in the duct as well (ref. 13).

In both references 11 and 13 the weight penalties involved more than just treatment weight. There were structural changes to the engine as well. To separate the weight due to treatment and the weight due to structure is impossible from those references alone. However, reference 14 indicates that two splitter rings weigh 150 pounds. To achieve 10 PNdB suppression in a long duct engine, the inlet needs only one ring and the duct and inlet walls must be treated. In this report it was assumed that this could be done for 150 pounds on a 53 inch diameter engine. Of this, 75 pounds was attributed to the single splitter and the other 75 pounds to the treatment of the duct and inlet walls. When 15 PNdB was required in this study, it was assumed that the extra inlet ring and additional duct treatment weigh 75 pounds for a 53-inch diameter engine.

Since most of the treatment is applied near the periphery of the engine, treatment weight was scaled directly with maximum engine diameter in this study. Using 80 inches as the reference diameter for this paper, the straight line of figure 7 was constructed through the two preceding points for a three-engine airplane.

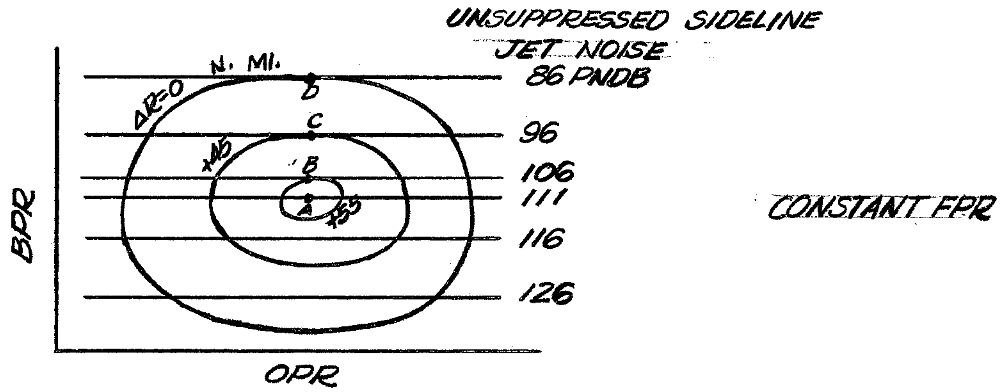
While 15 PNdB suppression is the maximum suppression demonstrated so far, greater amounts of suppression were assumed where necessary in this report to show the interaction of range and noise goals as low as FAR 36 minus 20 PNdB. The weights attributed to suppressions greater than 15 PNdB are an extrapolation through the two points just described in the construction of figure 7. It is unclear what the maximum amount of suppression achievable may be by 1978 or what the weight penalties due to such suppression may be. For this reason, as much as 40 PNdB suppression was postulated in this report when necessary.

The calculated noise numbers are subject to the assumptions relating cruise cycle parameters to the sea-level conditions. Since L/D at cruise was what sized the engines, the cycle parameters were input as cruise values. An engine component matching computer program verified that for the 200° F rise in T_4 assumed for sea-level-takeoff, very little change occurred in BPR, FPR, or OPR. To simplify the study, these parameters were assumed to be the same at takeoff and cruise. The slight adjustments needed to correct for more accurate component matching would cause only trivial changes in the noise calculations and corresponding cruise ranges.

Cycle Optimization at Various Noise Goals

In order to simplify the discussion later, a detailed explanation will be given in this part of the report to show how the optimum cycle is chosen for any noise goal.

First, a general computer program is used which calculates cruise engine performance, engine weight and total range. The program then goes to the sea-level-static and the lift-off conditions and calculates the engine performance and then the sideline jet noise at lift-off. The previously described assumptions relating cruise and sea-level-static engine parameters are used during this process. Compressor pressure ratio, fan pressure ratio and BPR are then varied over the range of interest. The resulting range and sideline jet noise can be plotted against BPR and OPR for each FPR, as shown in sketch A.



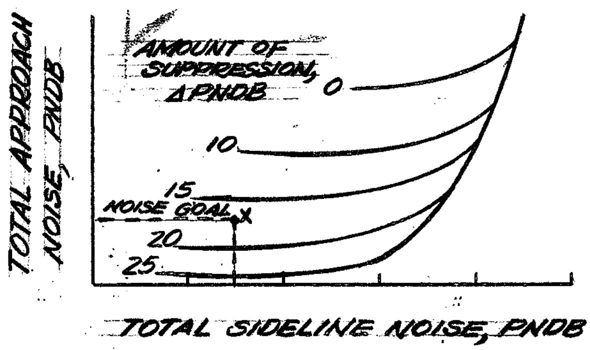
SKETCH A

A table is constructed from sketch A, listing the range-maximized engines at several levels of sideline jet noise (e.g., points A, B, C, D). Another entry is made in the table for unsuppressed turbomachinery noise from figure 6(b) at the proper FPR. Sketch A was for only one FPR. All of the engines, therefore, had the same unsuppressed machinery noise. This is because once the distance to the noise measuring station and the thrust have been specified, one curve can relate turbomachinery noise to FPR and the number of stages.

The perceived jet noise from points A, B, C, and D of sketch A is now added antilogarithmically to the machinery noise. Additional entries are made in the table for turbomachinery sideline noise assuming arbitrary amounts of suppression (e.g., 10, 15, 20, 25 PNdB). The jet noise from points A, B, C, and D of sketch A are again added, but this time to the suppressed machinery noise.

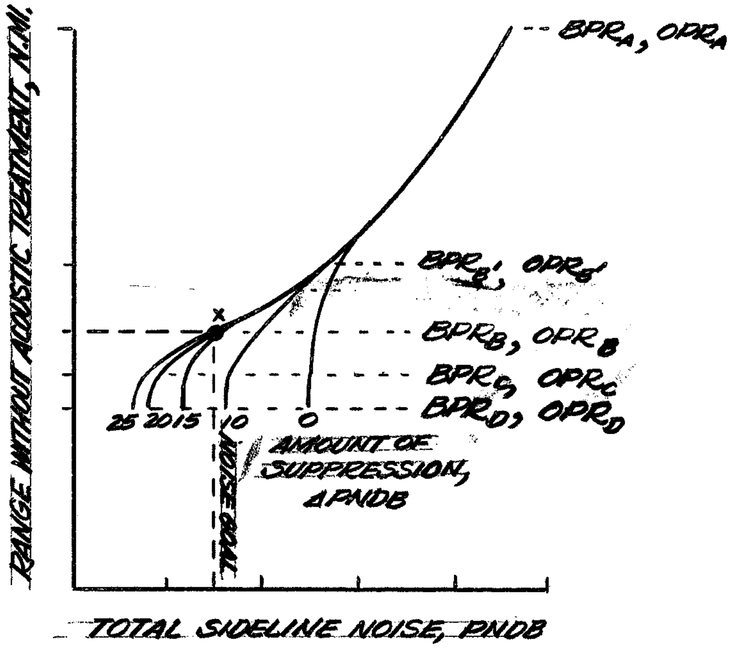
Another table is now constructed listing the same four engines. However, the approach jet and machinery noise (fig. 6(a)) are added this time. The same arbitrary amounts of machinery noise suppression are again assumed. The jet and fan machinery noise parameters are determined by using a computerized component matching program to obtain the important noise parameters at the part-power approach condition.

From the two preceding tables, two plots may be made. First, total approach noise is plotted against total sideline noise with the amount of machinery noise suppression as a parameter. A sketch of this is shown below:



SKETCH B

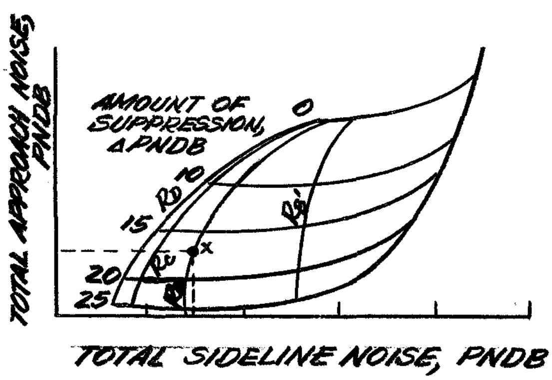
The next plot is of total range against total sideline noise with fan machinery noise suppression again as a parameter.



SKETCH C

The range is not corrected for noise suppression treatment weight at this time. A point is located on sketch B which just meets the takeoff and sideline noise goal (e.g., point X). The required amount of turbomachinery noise suppression is found to be about 18 PNdB at point "X" by interpolation. Sketch C is now entered at the proper sideline noise goal, and total range is read at the fan suppression level indicated from sketch B.

If lines of constant range from sketch C are superimposed on sketch B, the results look like sketch D.



SKETCH D

In general, point "X" is selected so as to just meet both noise goals. Meeting any sideline noise less than the sideline noise goal would result in a loss in range without any forseeable benefits. Meeting any approach noise less than the approach noise goal would offer only trivial range increases and increase the amount of machinery noise suppression required. The additional weight due to the greater suppression required would nullify any apparent range increase.

The optimum cycle parameters can be determined from sketch C once point "X" has been located. Each horizontal constant range line on this sketch represents a particular engine from sketch A (e.g., points A, B, C, and D). The BPR and OPR of each engine is labled on sketch C at the proper range. In this example where point "X" was selected, the optimum cycle parameters are BPR_B and OPR_B.

With the proper amount of suppression now known, figure 7 may be used to find the machinery noise suppression weight penalty to the airplane. This is for engines with a maximum diameter of 80 inches. If the optimum cycle had a diameter different from 80 inches, the weight read from figure 7 is scaled directly with maximum diameter. The final weight penalty then is added to the weight of the airplane at the end of cruise. This term appears in the Breguet range equation. Thus the range at point "X" is reduced to some lower level than that shown in sketch C.

This entire process was repeated for all the engines and noise goals. Thus the optimum cycles were identified, the proper amount of suppression determined, and the final range arrived at.

RESULTS AND DISCUSSION

General Analysis With Variable FPR and Constant T_4

The reference $T_{4,sls}$ was chosen to be 2300° F in this report. This is typical of modern engines. Higher values of $T_{4,sls}$ were not investigated in this section of the report because reference 2 had predicted very little range increase as $T_{4,sls}$ was increased from 2000° to 2400° F at a noise goal of 106.5 PNdB. Reference 2 also showed that if the FPR increased beyond 1.7, the 106 PNdB noise goal could not be met with only 15 PNdB of machinery noise suppression.

A more general view of suppression capability was taken in this report. While 15 PNdB is still recognized as the maximum demonstrated to date, advanced technology by the year 1978 may allow greater amounts of suppression. There is a lot of uncertainty in the situation, but for this report turbomachinery noise suppressions as high as 40 PNdB were assumed just to show what suppression would be required at various noise goals. This reopens the question of what limit should be placed on FPR and/or just how low a noise goal could be met.

Figure 8 is a plot of constant range contours and constant unsuppressed jet noise levels against OPR and BPR. The FPR for this figure is 1.7 and the T_4 is 2300° F. The reference range is 3000 nautical miles. None of the ranges shown in this figure have any sort of penalty for acoustic treatment, as discussed in the METHOD OF ANALYSIS. These plots are referred to as "thumbprints" in the rest of the report.

The maximum range shown in figure 8 is 3320 nautical miles at the center contour. The sideline jet noise at this point is 126 PNdB - well above the 106.5 PNdB goal of FAR-36. The minimum jet noise shown on the figure is 86 PNdB. This level is a minimum jet noise for this FPR because of the duct jet velocity associated with an FPR of 1.7. Notice that the change in range is not too great between contours near the center of the plot and that large variations in OPR and BPR will result in nearly the same range. However, such large variations do not necessarily result in the same jet noise. A thumbprint like this was drawn for each FPR and each T_4 examined in this report. They were used, as described in the METHOD OF ANALYSIS, to help determine the best range at any given level of unsuppressed jet noise.

Engine parameters for no noise constraints. - Figure 9 is a plot of total range against FPR for several noise goals and for an unconstrained case. Where noise goals are applied, the range shown reflects the weight penalties due to suppression material.

The unconstrained case will be discussed first since it will be used as a reference for any penalties mentioned from this point forward. By increasing the FPR from 1.70 to 3.0, the range may be increased from 3320 to 3710 nautical miles. The optimum engine, which will be used as a reference, would have an FPR of 3.0, since range is maximized at 3710 nautical miles by this choice. This engine would have a BPR of 2.4 and an OPR of 30.5. This can be seen from figures 10(a) and (b), where optimum BPR and OPR are plotted against FPR. The reason that range tends to increase with FPR is that better sfc's are obtained as FPR is increased from 1.7 to 2.5. This offsets the increase in engine weight due to increased engine airflow as shown in figure 10(f). When the FPR was increased from 2.5 to 3.0 the gains in range were obtained with increasing difficulty. At a FPR of 3.0, the BPR was forced back down to

2.4 which reduced the engine airflow and size some (figs. 10(f) and (g)) and increased the L/D. However, the sfc increased. If the FPR were increased beyond 3.0, the range would be less than 3710 miles. At an FPR of 3.0 this reference airplane would have a noise level of about 130.0 PNdB during approach and about 120.0 PNdB sideline noise during lift-off. These noise levels combine both jet and machinery noise.

Engine parameters for 106 PNdB. - When a noise goal of 106 PNdB is applied to the engines, there is a range penalty involved even though the engines are reoptimized as they always were in this study. Figure 9 shows that at an FPR of 1.70, the 106 PNdB noise goal can be met with a range of 3210 miles. This is a range penalty of 500 miles from the reference range of 3710 miles. From figures 10(a) and (b) the engine needed to accomplish this would have a BPR of 4.80 and an OPR of 32. Seven PNdB of turbomachinery noise suppression would be required, which would penalize the airplane weight about 500 pounds (figs. 10(c) and (d)). From parts (e), (f), and (g) of figure 10, it can be seen that the airplane would have a $\left(F_N/W_G\right)_{sls}$ of 0.33 and the engines would have a corrected $\left(W_a\right)_{sls}$ of 1280 pounds per second and a diameter of 86 inches. The suppression quoted was for a single stage fan. If a two-stage fan were used with an FPR of 1.7, the range would drop another 20 miles (fig. 9). This is because the higher turbomachinery noise of a two-stage fan (fig. 6) requires another 8 PNdB of suppression. The total suppression would then be 15 PNdB as shown in figure 10 (c). This increases the weight penalty from 500 to 1100 pounds (fig. 10(d)) and accounts for the 20-mile decrease in range. The other cycle parameters remain the same.

The maximum range attainable with a noise goal of 106 PNdB is 3635 nautical miles at an FPR of 2.9. This is a penalty of only 75 miles. The FPR cannot be increased beyond 2.9 because the duct jet noise would exceed 106 PNdB. From figure 9 it looks as if increasing the FPR beyond 2.9 would not help the range in any case. The optimum cycle parameters, and the noise and airplane-related parameters can be found in figure 10. The engine would have a BPR of 2.5, an OPR of 30.6, require 34 PNdB of machinery noise suppression at a weight penalty of 1750 pounds, provide the airplane with an $\left(F_N/W_G\right)_{sls}$ of 0.255, and need a corrected $\left(W_a\right)_{sls}$ of 750 pounds per second, which would result in an engine diameter of 64 inches.

Engine parameters for 96 PNdB. - The maximum range that can be attained if a 96 PNdB noise goal is set is 3380 nautical miles. This is a penalty of 330 miles. An engine with an FPR of 2.08 is required. Higher FPR's would be desirable because of greater range, but if the FPR is greater than 2.08, the duct jet noise would be higher than 96 PNdB. The fan is assumed to be a two-stage fan at this pressure ratio. From figure 10, the optimum cycle and noise parameters can be found. The engines would have a BPR of 4.1, an OPR of 30.0, require 28.0 PNdB of machinery noise suppression at a weight penalty of 2000 pounds, provide the airplane with an $\left(F_N/W_G\right)_{sls}$ of 0.30, and need a corrected $\left(W_a\right)_{sls}$ of 1080 pounds per second each. Engine maximum diameter would be 78 inches.

Engine parameters for 86 PNdB. - It can be seen from figure 9 that if the noise goal is 86 PNdB the maximum FPR that can be used is 1.70. Higher FPR's would yield greater range; however, if the FPR is greater than 1.70, the duct jet noise will exceed 86 PNdB. The maximum range that can be attained with this noise goal is 3060 miles. The engine would have a one-stage fan. From figure 10, the optimum engine for this noise goal would have a BPR of 6.6, an OPR of 30.0, require 40 PNdB of machinery noise suppression at a weight penalty of 3200 pounds, provide the airplane with an $\left(F_N/W_G\right)_{sls}$ of 0.34, and need a corrected $\left(W_a\right)_{sls}$ of 1520 pounds per second each. An engine diameter of 95 inches would result.

Minimum noise using only 15 PNdB machinery noise suppression. - Based on the maximum machinery noise suppression available today (about 15 PNdB), the 106 PNdB noise goal can be met. Figure 9 shows a limiting line for 15 PNdB of machinery noise suppression. It crosses the

106 PNdB goal line at an FPR of 1.7. Since it crosses at the bottom of the vertical jog in the curve for a 106 PNdB goal, this means that it is a two-stage fan. The range here is 3190 miles. A one-stage fan could meet the 106 PNdB goal using less than 15 PNdB of machinery noise suppression and increase the range to 3210 miles. By interpolation it can be determined that the lowest noise goal that can be met with 15 PNdB of acoustic treatment with a one-stage fan at an FPR of 1.70 is 98 PNdB. This point is marked by the square on figure 9. The range is 3170 nautical miles. From figure 10, by interpolation, the engines would have a BPR of 5.4, an OPR of 31.2, require 15 PNdB of machinery noise suppression at a weight penalty of 1100 pounds. The aircraft would have an $\left(F_N/W_G\right)_{sls}$ of 0.335 and the engines would require a corrected $\left(W_a\right)_{sls}$ of 1380 pounds per second each. An engine diameter of about 90 inches would result. If 15 PNdB of suppression is all that is available, it would make sense to design for the 98 PNdB noise level instead of 106 PNdB since the additional range penalty is only 40 miles if one-stage fans are used.

Range with the use of a jet noise suppressor. - The maximum FPR is limited at each noise goal by duct jet velocity, since jet velocity is the most sensitive parameter in the jet noise calculation. In this section of the report, a jet noise suppressor was assumed which would reduce the jet noise by 10 PNdB from both streams during approach and takeoff. This was done to see if there were particular noise goals that could be helped by a jet noise suppressor. At any noise goal, higher FPR's may now be considered because the duct jet noise has been reduced by 10 PNdB. The jet suppressors considered in this report were assumed to weigh nothing and have no losses so that the maximum possible gains could be shown.

Figure 11 is a plot similar to figure 9. However, in figure 11, in addition to the machinery noise suppression assumed (up to 40 PNdB), 10 PNdB of jet noise suppression was also assumed, as just discussed. Since duct jet noise limited the FPR to some level in figure 9, it will limit FPR to some higher value in figure 11. For example, the 86 PNdB noise goal limited FPR to 1.70 in figure 9, but in figure 11 it limited FPR to 2.13. Since the jet noise suppressor was assumed to weigh nothing, the higher FPR's in figure 11 will allow a range advantage over figure 9 at any noise goal.

Range-noise trade off. - In order to summarize the results thus far, figure 12 was plotted. This figure is a plot of maximum range against noise goal for three different situations. The lowest curve A is for engines without jet noise suppressors and having a maximum of 15 PNdB machinery noise suppression. Curve B is for engines without jet noise suppressors but with up to 40 PNdB of machinery noise suppression. Curve C has up to 40 PNdB of machinery noise suppression and a weightless jet noise suppressor, as previously described, which reduces jet noise by 10 PNdB.

The most significant comparisons to be made from figure 12 are summarized in Table I. From figure 12 and table I it can be seen that, at a noise goal of 106 PNdB, a range penalty of 500 miles results if you are forced to stay on curve A. By switching to curve B, this penalty is reduced to 75 miles. The machinery noise suppression required at this point is 34 PNdB. This is considerably above the 15 PNdB demonstrated to date. Using only 25 PNdB machinery noise suppression and the 10 PNdB jet noise suppressor the range penalty can be further reduced to 55 miles (curve C). Thus, jet noise suppressors do not allow much of a gain in range at this noise goal but do allow reductions to be made in the amount of acoustic treatment required to suppress machinery noise.

The lowest noise goal that can be achieved using only 15 PNdB of machinery noise suppression is 98 PNdB, the circled point on curve A. If only 15 PNdB of machinery noise suppression is available, this may be a good trade since the range penalty is only 40 nautical miles more than at the 106 PNdB goal.

As the noise goal is lowered toward 86 PNdB, it becomes increasingly obvious that the jet noise suppressor allows significantly more range than just the turbomachinery noise suppression alone (curve C compared to curve B). At 86 PNdB, the range penalty is 650 miles if curve B is used but only 300 miles if curve C is used. Of course, the jet noise suppressors have been assumed to be weightless. It would in fact, weigh something, and this would reduce the potential gains in a real life situation. However, the weight of the jet suppressors would have to be somewhere between 8000 and 9000 pounds if the entire range advantage were to be eliminated. This is about 45 percent of the installed weight of the engines, not including the weight of the suppressors. To determine what the actual weight of a jet noise suppressor would be is not within the scope of this report.

All of the engine cycle parameters, suppression required, approach and sideline noise are summarized in table I. Most of the values listed in the table can be read from figures 9 to 11. Using these figures, many different trade-offs can be made. These were only meant to be a sampling.

Range With Variable T_4 and Constant FPR

The assumption up to now had been that increasing T_4 did not improve range very much when noise constraints were applied. This assumption was based on reference 2 where $T_{4,sls}$ was varied from 2000° to 2400° F with no significant increase in range at a noise goal of 106.5 PNdB. In this study it was decided to vary $T_{4,sls}$ from the reference 2300° F up to 3000° F. The thought was that this large increase in T_4 might show more improvement in range. The T_4 was varied at an FPR of 1.70 only, so that noise goals as low as 86 PNdB could be examined. From the preceding part of this report it was known that at FPR's greater than 1.70 the 86 PNdB goal could not be met with only 40 PNdB of machinery noise suppression. Jet noise suppressors were not considered in this section. If they had been, the results would have shown a level of range somewhat higher, but the trends with T_4 would be the same.

Figure 13 shows the results of this part of the study. Total range, including suppression weight penalties, is plotted against $T_{4,sls}$ for three noise goals. The results can best be summarized by saying that the range does not show any significant change for the T_4's investigated at any of the noise goals. This is not too surprising considering some of the differences between this study and reference 2. In this study, the turbine cooling bleed schedule was slightly steeper with T_4 than in reference 2. Also, the engines in this report were of a more advanced weight technology than in reference 2 (i.e., year 1978 instead of 1974). The lighter engine weight tends to reduce the importance of increasing T_4. This is because most of the gains in range at higher T_4 are due to the smaller engine size (and thus weight) required. The smaller engines came as a result of higher F_N/W_a at higher T_4's. Thus, the effect of a certain percent improvement in F_N/W_a does not save as much engine weight in this report as in reference 2 due to the lower engine base weights.

Range-noise tradeoff. - Table II was constructed to show the tradeoff range against noise for the lowest and highest T_4 investigated. The reference range is the same as for the first part of the report (i.e., 3710 n. mi.).

When the FPR is limited to 1.70, as it was in this section of the report, some large range penalties are involved. If the goal is set at 106 PNdB, the minimum range penalty at a $T_{4,sls}$ of 2300° F would be 500 miles. From table II, the optimum OPR would be 31.8 and the BPR would be 4.8. Only 7 PNdB of machinery noise suppression would be required and the noise would be 106 PNdB at both measuring points. Increasing $T_{4,sls}$ to 3000° F would cause the range penalty to increase another 25 miles without any offsetting benefits.

If a 96-PNdB goal is selected, table II shows that a $T_{4,sls}$ of 3000° F will provide no more range than a $T_{4,sls}$ of 2300° F. Therefore, once again the 2300° F case would probably be selected. The engines would require an OPR of 31.3 and a BPR of 5.60. Turbomachinery noise suppression required would be only 17 PNdB which very well could be available by 1978. The noise at both measuring stations would be 96 PNdB.

At a noise goal of 86 PNdB, the range penalty would be 645 miles at a $T_{4,sls}$ of 2300° F and 615 miles at a $T_{4,sls}$ of 3000° F. While the penalty is less at 3000° F, the extra 30 miles is not worth trying for, considering the greater uncertainties to be encountered. If a $T_{4,sls}$ of

2300° F were selected, the engine would have an OPR of 30.5, a BPR of 6.8, and require 40 PNdB of machinery noise suppression. The noise at approach would be 78 PNdB and at takeoff it would be 86 PNdB.

Perturbation of Engine Design Parameters

To find out how sensitive range was to our assumed engine design parameters, a sensitivity study was done for a reference engine. The reference engine had a BPR of 4.8, FPR of 1.7, OPR of 31.0 and a T_4 of 2300° F. This engine was chosen because it is the optimum engine for a noise goal of 106 PNdB if 15 PNdB is accepted as a limit on turbomachinery noise suppression.

The bar graph (fig. 14) shows the range increases for a 0.01 change in each of the variables. Also shown is the range increase for a 10-percent change in bare engine weight. These bars may be interpreted as negative changes in range if the variable is changed 0.01 in the opposite direction shown. The results are also approximately linear with a change in the variable up to ±0.05. Outside this range, the accuracy decreases.

Only one parameter was varied at a time. Each time one was varied a new range resulted. The jet noise also varied slightly as each parameter changed. This is why the input assumptions are important when trying to attain a certain jet noise.

By far the most sensitive of these parameters was the duct nozzle gross thrust coefficient. A one-percent change in it produced a 100-mile change in range. Inlet pressure recovery was also quite sensitive. A one-percent change in it produced a 65-mile change in range. Changes in engine weight were also found to produce significant changes in range. A ten-percent change in base engine weight produced a 63-mile change in range.

The reference values of the parameters are typical of well-designed engines and engine installations today. It will most likely be more difficult to achieve these values when sound suppression material is used in the engines. Nevertheless, they are goals to strive for. It is obvious from the bar graph that care will have to be given to the inlet, duct, and duct nozzles when treating for noise since these areas are the most sensitive.

Constant L/D Optimization

As a final perturbation to the basic study, the engines were reoptimized at a $T_{4, sls}$ of 2300^{o} F and an FPR of 1.7 while holding the L/D at the reference value of 16.8. This was done so that the optimization could be compared to the optimization in the first part of this report, and to the optimization done in reference 2. These comparisons will show how sensitive the optimum cycle is to the input assumptions. Listed below are the inputs and results for the three cases.

	This study	This study	Reference 2
Year of first flight	1978	1978	1974
L/D/(function of diameter)	16.54/(yes)	16.8/(no)	16.8/(no)
$\beta_{HP, T}/\beta_{LP, T}$	7.5/0	7.5/0	0/7.0
Inlet pressure recovery	0.98	0.98	1.00
η_{fan}	0.88	0.88	0.83
$\eta_{compressor}$	0.89	0.89	0.85
$\eta_{combustor}$	0.99	0.99	0.985
Pressure across combustor	0.96	0.96	0.94
Duct pressure ratio	0.94	0.94	0.96
Exhaust nozzle $C_{FG, P}$, $C_{FG, D}$	0.98	0.98	0.985
$T_{4, sls}$, °F	2300	2300	2300
Range, n. mi.	3210	3295	3090
BPR	4.8	5.60	4.25
FPR (one stage fan)	1.70	1.70	1.70
OPR	31.8	30.0	26.0
Noise goal, PNdB	106	106	105
Weight of bare engine, lb	6064	5931	6460
Weight of three installed engines, lb	30358	30653	30446
Cruise SFC, hr^{-1}	0.719	0.709	0.757
Machinery suppression required, PNdB	7	7	10
Corrected ($W_{a, sls}$), lb/sec	1290	1370	1190

Comparing the first two columns, the only difference in the input is the assumption of L/D. When the engine drag and thus airplane L/D vary with engine diameter, the best range that can be attained at FPR of 1.70 is 3210 miles (first column). The optimum BPR is 4.8 and the optimum OPR is 31.8. The other engine parameters are also listed in column 1. Fixing the L/D at 16.8 (column 2) causes the engine to reoptimize. The optimum BPR increases from 4.8 (column 1) to 5.6 (column 2). The OPR decreases from 31.8 to 30.0 and the range increases from 3210 to 3295 nautical miles. The most significant of these changes is the BPR. This comparison shows that the optimum BPR is quite sensitive to the assumptions regarding how drag varies with different engines.

There are several input differences between columns 2 and 3, but the L/D was fixed at 16.8 in both cases. In this study (column 2), the year of first flight was four years later than in reference 2 (column 3). This tended to reduce the engine weight which made the SFC more important. This trend toward lower SFC forced the optimum BPR and OPR to increase. Other things that tended to increase thrust per pound of air, lower SFC, and make higher BPR's more attractive were the improved efficiencies of the fan and compressor. There are some other changes between columns 2 and 3, but their impact on the results was relatively small compared to those just mentioned.

All of the changes between columns 2 and 3 result in a range improvement of 205 nautical miles for this study (column 2) compared to reference 2. Compared to reference 2, the optimum BPR increased from 4.25 to 5.6, OPR increased from 26 to 30 and SFC decreased from 0.757 to 0.709 hour^{-1}. This SFC decrease alone accounts for the range increase. The 1978 engine is lighter than its 1974 counterpart. However, the installed weight of the 1978 engine is slightly more than the installed weight of the 1974 engine because it is a function of design corrected $W_{a,sls}$, as well as bare engine weight. The design corrected $W_{a,sls}$ of the 1978 engine is 15 percent greater than the 1974 engine. This comparison shows that the optimum BPR is also very sensitive to the assumptions regarding weight of the engine and design component efficiencies.

CONCLUDING REMARKS

A parametric engine study was made for an advanced technology transport using the Whitcomb supercritical wing. Cruise was chosen to be at Mach 0.98 at an initial cruise altitude of 40 000 feet. Advanced engine weight technology compatible with a first flight in 1978 was assumed. A takeoff gross weight (TOGW) of 386 000 pounds was selected for this 300-passenger airplane in order to provide a range of 3000 to 4000 nautical miles. As the engine design parameters were varied, range (the figure of merit) was allowed to vary. Only three-engine airplanes were studied. The engines were sized for cruise and the payload was fixed at 60 000 pounds. Engine weight was assumed to vary as a function of the sea-level-static engine parameters as well as year of first flight. Since TOGW, payload, and airframe weight were fixed, the sum of engine and fuel weight was also constant.

Fan pressure ratios (FPR) of 1.7, 2.5, and 3.0 were examined. At each FPR the bypass ratio (BPR) and overall pressure ratio (OPR) were optimized for maximum range with takeoff turbine-rotor-inlet-temperature (T_4) fixed at 2300° F.

Each of the engines in this study was sized for cruise with T_4 reduced by 200° F from the takeoff value. The values of sea-level-static BPR, FPR, and OPR were verified to be about the same as the values at cruise. A correction was made, however, for the difference in corrected airflow between cruise and sea-level-static. Detailed engine cycle calculations were made for approach. All of the airplanes were assumed to use 20 000 pounds of fuel for climb and 2000 pounds of fuel for letdown. Reserve fuel was always 18 percent of the total fuel load. Despite the approximations, it is felt that the results are valid and point the way toward selection of an engine at any desired noise goal between 86 and 106 PNdB at the measuring stations specified in FAR Part 36.

One of the major observations to be made from this study is that range increases as FPR is increased and maximizes at an FPR of 3.0 when no noise constraints are imposed. The range at this point would be 3710 nautical miles. If the amount of machinery noise suppression is limited to 15 PNdB, the minimum noise goal that can be met is 98 PNdB. The engine would have an FPR of 1.7 (the maximum for a one-stage fan) and a range of 3170 miles. If a goal of 106 PNdB is desired, the machinery noise suppression required would only be 7 PNdB with a one-stage fan. The range would be 3210 miles. No range advantage would accrue from the use of a two-stage fan when a 106-PNdB goal is imposed and acoustic treatment is limited to 15 PNdB.

If the amount of turbomachinery noise suppression available is greater than 15 PNdB, some tradeoffs are available. With a noise goal of 106 PNdB, a range of 3635 nautical miles may be attained. This requires an FPR of 2.9 and 34 PNdB of machinery suppression. A noise goal of 87 PNdB could have been met with a range of 3075 miles. This would have required an FPR of 1.7 and 26 PNdB of machinery noise suppression. While such an airplane has an additional range penalty compared to the 106 PNdB example, the noise level is reduced by 19 PNdB. Involved here is a tradeoff between the economic benefits of improved range and the social benefits of reduced noise.

Another possibility examined in this report was the use of a jet noise suppressor. At a noise goal of 106 PNdB, the use of a 10 PNdB jet noise suppressor yields a gain of only 20 miles. At a goal of 86 PNdB the range can be improved 350 miles by the use of a 10-PNdB jet noise suppressor. The suppressors were assumed to be weightless. The weight of the actual suppressor would reduce this range improvement some, but the total increase in airplane empty weight would have to be about 8000 pounds to nullify the entire 350-mile improvement. If a jet noise suppressor capable of more than 10 PNdB suppression were assumed, the theoretical maximum gains in range could be greater than 350 miles with a noise goal of 86 PNdB. However, the 106 PNdB noise goal still could not benefit from such a jet noise suppressor.

A previous study concluded that increasing $T_{4,sls}$ did not significantly improve the range at a noise goal of 106.5 PNdB. These conclusions were re-verified in this study even though more realistic ground rules were established. The FPR was fixed at 1.7 so that very low noise goals could be examined. The results of this study indicate that at all noise goals between 106 and 86 PNdB there are no significant improvements in range when the $T_{4, sls}$ is increased from 2300° to 3000° F.

Range sensitivity to certain inputs was examined. The reference one-stage fan engine had a $T_{4, sls}$ of 2300° F, an FPR of 1.7, an OPR of 31, and a BPR of 4.8. Inlet recovery; fan, compressor, combustor, and both high- and low-pressure turbine efficiencies; turbine cooling bleed; pressure loss in the primary combustor and duct; nozzle gross thrust coefficient; and, finally, engine weight were individually varied.

By far the most sensitive of these parameters was the duct nozzle thrust coefficient. A one-percent change in it produced a 100-mile change in range. Inlet pressure recovery was also quite sensitive. A one-percent change in it produced a 65-mile change in range. Changes in engine weight were also found to produce a significant change in range. A ten-percent change in bare engine weight produced a 63-mile change in range. The rest of the parameters produced 30-mile changes in range, or less. The results of this study indicate that great care should be used when integrating the sound suppression material with the inlet, ducts, and nozzles. As is usually the case, engine weight should be kept to a minimum.

A final perturbation involved the reoptimization of engines with an FPR of 1.7 and a $T_{4, sls}$ of 2300° F when it was assumed that the L/D of the airplane did not vary with engine diameter. While this may not be realistic due to nacelle skin friction drag changes with surface area, it did show that the optimum BPR was quite sensitive to the L/D variation assumed. Comparing this constant L/D study to the results of a previous study showed that the optimum BPR is also quite sensitive to the assumed fan and compressor efficiencies and the level of engine weight technology assumed.

REFERENCES

1. Thomas, B. K., Jr.: New Wing Promises Design Breakthrough. Aviation Week & Space Tech., vol. 87, no. 4, July 24, 1967, pp. 25-26.

2. Whitlow, John B., Jr.; Kraft, Gerald H.; and Civinskas, Kestutis C.: Parametric Engine Study For A Mach 0.98 Commercial Air Transport. NASA TM X-52961, 1971.

3. Anon.: U. S. Commercial Transports. Aviation Week & Space Tech., vol. 92, no. 10, Mar. 9, 1970, p. 121.

4. McKinney, John S.: Simulation of Turbofan Engine. Part I. Description of Method and Balancing Technique. Rep. AFAPL-TR-67-125, pt. 1, Air Force Aero Propulsion Lab., Nov. 1967.

   McKinney, John S.: Simulation of Turbofan Engine. Part II. User's Manual and Computer Program Listing. Rep. AFAPL-TR-67-125, pt. 2, Air Force Aero Propulsion Lab., Nov. 1967.

5. Gerend, Robert P.; and Roundhill, John P.: Correlation of Gas Turbine Engine Weights and Dimensions. Paper 70-669, AIAA, June 1970.

6. Anon.: Jet Noise Prediction. Aerospace Information Report 876, SAE, July 10, 1965.

7. Anon.: Definitions and Procedures for Computing the Perceived Noise Level of Aircraft Noise. Aerospace Recommended Practice 865, SAE, Oct. 15, 1964.

8. Kramer, James J.; Chestnutt, David; Krejsa, Eugene A.; Lucas, James G.; and Rice, Edward J.: Noise Reduction. Aircraft Propulsion. NASA SP-259, 1971, pp. 169-209.

9. McPike, A. L.: Recommended Practices for Use in the Measurement and Evaluation of Aircraft Neighborhood Noise Levels. Paper 650216, SAE, Apr. 1965.

10. Watson, H. A., Jr.; Thompson, J. D.; and Rucker, Carl E.: Structural and Environmental Studies of Acoustical Duct-Lining Materials. Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft. NASA SP-189, 1968, pp. 63-101.

11. Pendley, Robert E.: Introduction to McConnel Douglas Program. NASA Acoustically Treated Nacelle Program. NASA SP-220, 1969, pp. 19-28.

12. Feiler, Charles E.; Rice, Edward J.; and Smith, L. Jack: Performance of Inlet Sound Suppressors. Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft. NASA SP-189, 1968, pp. 53-62.

13. Atvars, Janis; Mangiarotty, R. A.; and Walker, David Q.: Acoustic Results Of 707-320B Airplanes with Acoustically Treated Nacelles. NASA Acoustically Treated Nacelle Program. NASA SP-220, 1969, pp. 95-108.

14. Pendley, Robert E.: Design Concepts. Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft. NASA AP-189, 1968, pp. 113-129.

TABLE I. - RANGE-NOISE TRADEOFF, TURBINE ROTOR-INLET TEMPERATURE = 2300°F

CURVE	REF. POINT	A		B			C		
NOISE GOAL, PNDB	NONE	106	98	106	96	86	106	96	86
MAXIMUM RANGE, N.MI	3710	3210	3170	3635	3380	3060	3655	3620	3410
RANGE PENALTY, N.MI	0	500	540	75	330	650	55	90	300
OPTIMUM FPR	3.0	1.7	1.7	2.9	2.08	1.7	3.0	2.72	2.16
OPTIMUM OPR	30.5	31.8	31.1	30.6	31.0	31.0	30.5	30.7	30.9
OPTIMUM BPR	2.4	4.8	5.5	2.45	4.1	6.5	2.4	2.7	3.9
JET NOISE SUPP.	0	0	0	0	0	0	10	10	10
MACHINERY NOISE SUPP.	0	7	15	34	28	40	25	38	40
NO. OF FAN STAGES	2 OR 3	1	1	2 OR 3	2	1	2 OR 3	2 OR 3	2
APPROACH NOISE, PNdB	130	106	98	106	96	78	106	96	86
SIDELINE NOISE, PNdB	120	106	98	106	96	86	99	94	86

TABLE II. - RANGE-NOISE TRADEOFF, FAN PRESSURE RATIO = 1.70

	REF. POINT						
$T4_{SLS}$ °F	2300	2300			3000		
NOISE GOAL, PNDB	NONE	106	96	86	106	96	86
MAXIMUM RANGE, N.MI.	3710	3210	3155	3065	3185	3155	3095
RANGE PENALTY, N.MI.	0	500	555	645	525	555	615
OPTIMUM FPR	3.0	1.7	1.7	1.7	1.7	1.7	1.7
OPTIMUM OPR	30.5	31.8	31.3	30.5	36	36	36
OPTIMUM BPR	2.4	4.8	5.6	6.8	9.0	9.0	9.3
MACHINERY NOISE SUPP.	0	7	17	40	7	17	40
NO. OF FAN STAGES	2 or 3	1	1	1	1	1	1
APPROACH NOISE, PNDB	130	106	96	78	106	96	78
SIDELINE NOISE, PNDB	120	106	96	86	99	91	86

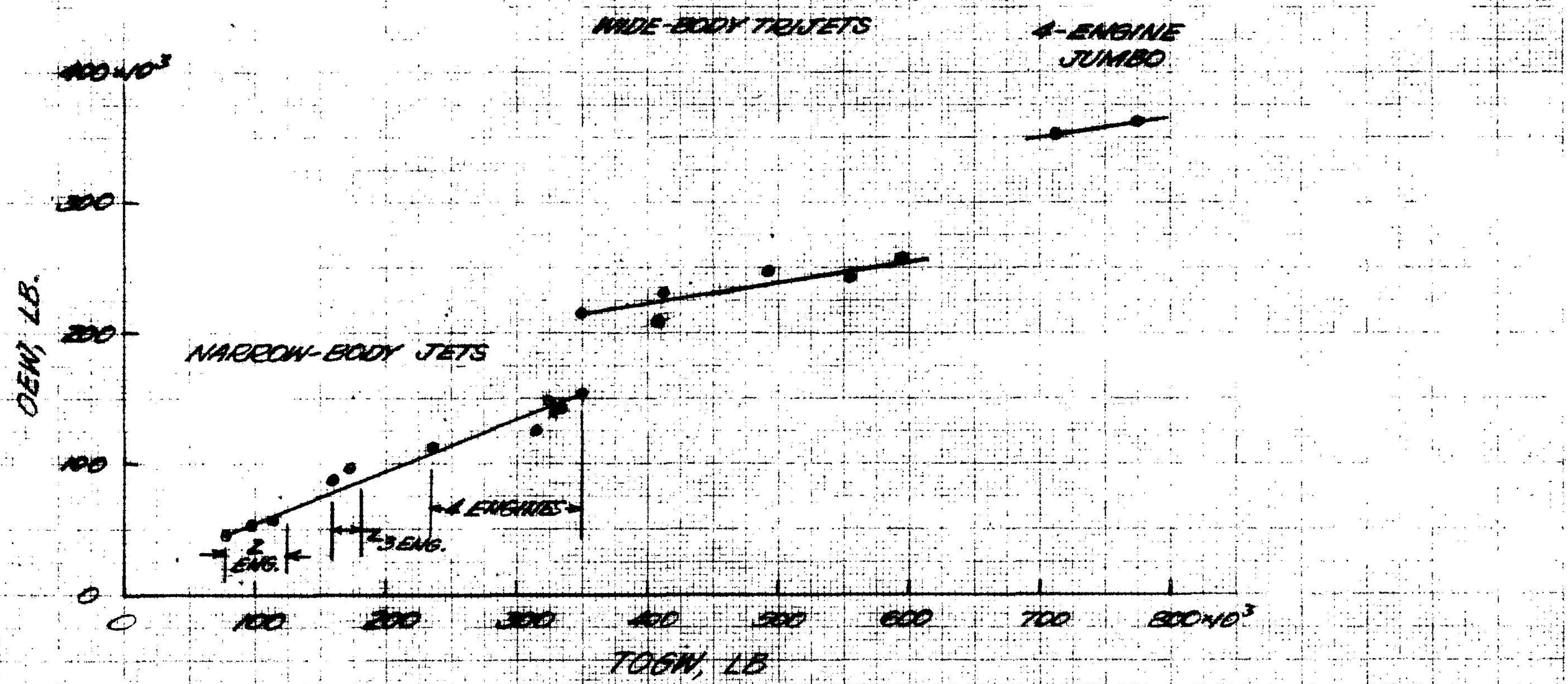


FIGURE 1.- WEIGHTS OF TURBOFAN-POWERED SUBSONIC TRANSPORTS. (DATA FROM REF. 2)

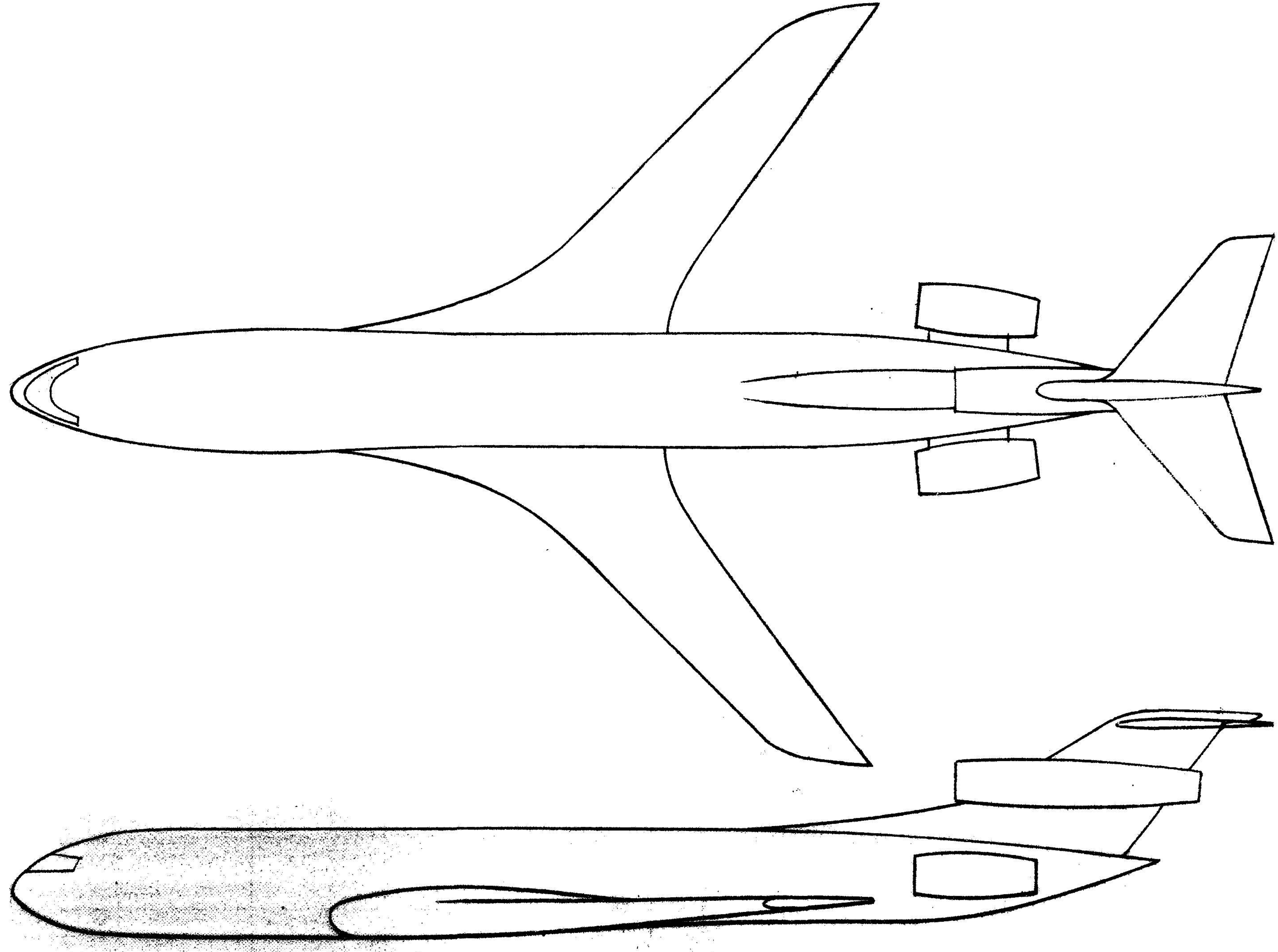


FIGURE 2.— SKETCH OF CONCEPTUAL MACH 0.98 TRI-JET TRANSPORT.

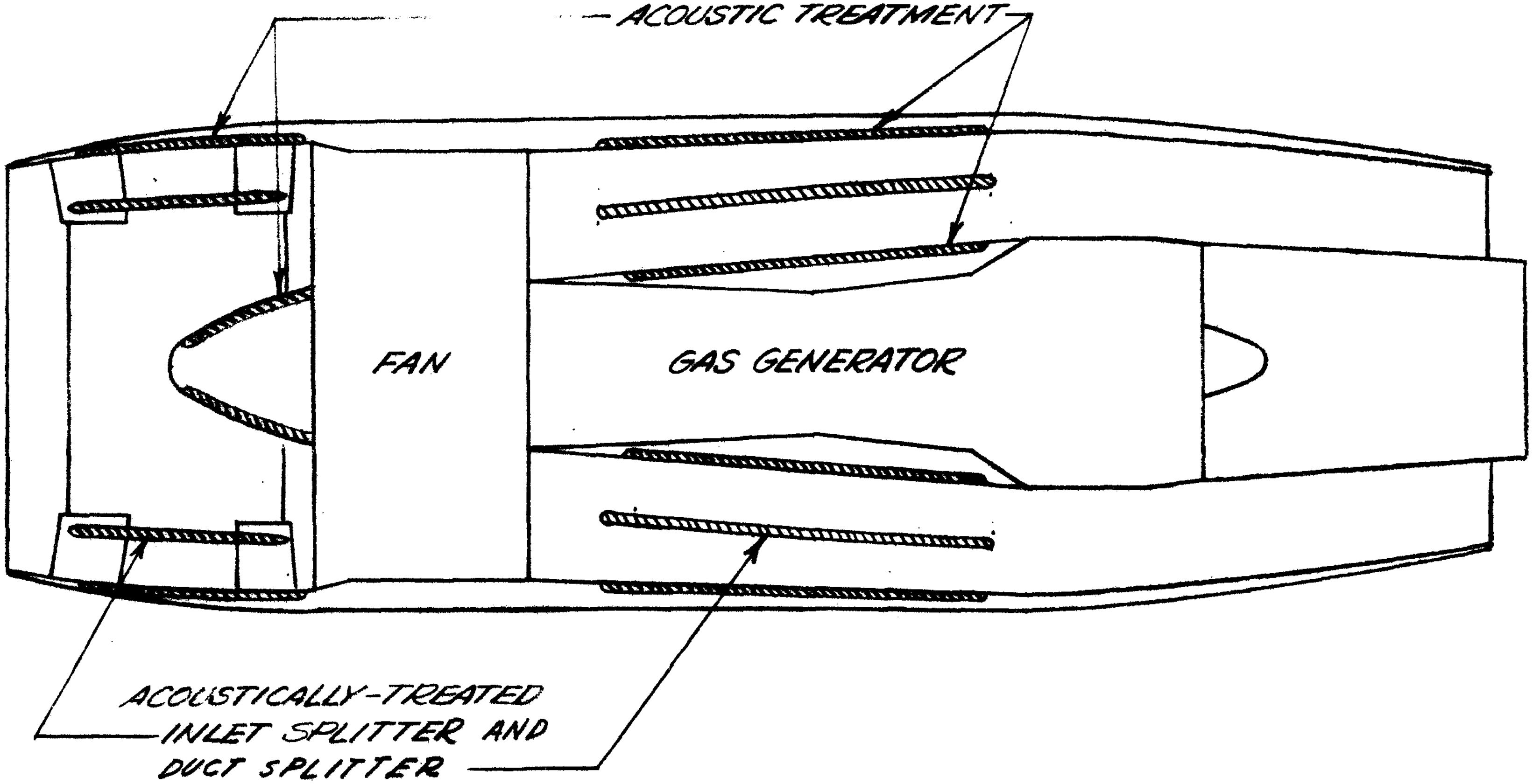


FIGURE 3. – SKETCH OF TURBOFAN ENGINE INSTALLATION WITH ACOUSTIC TREATMENT.

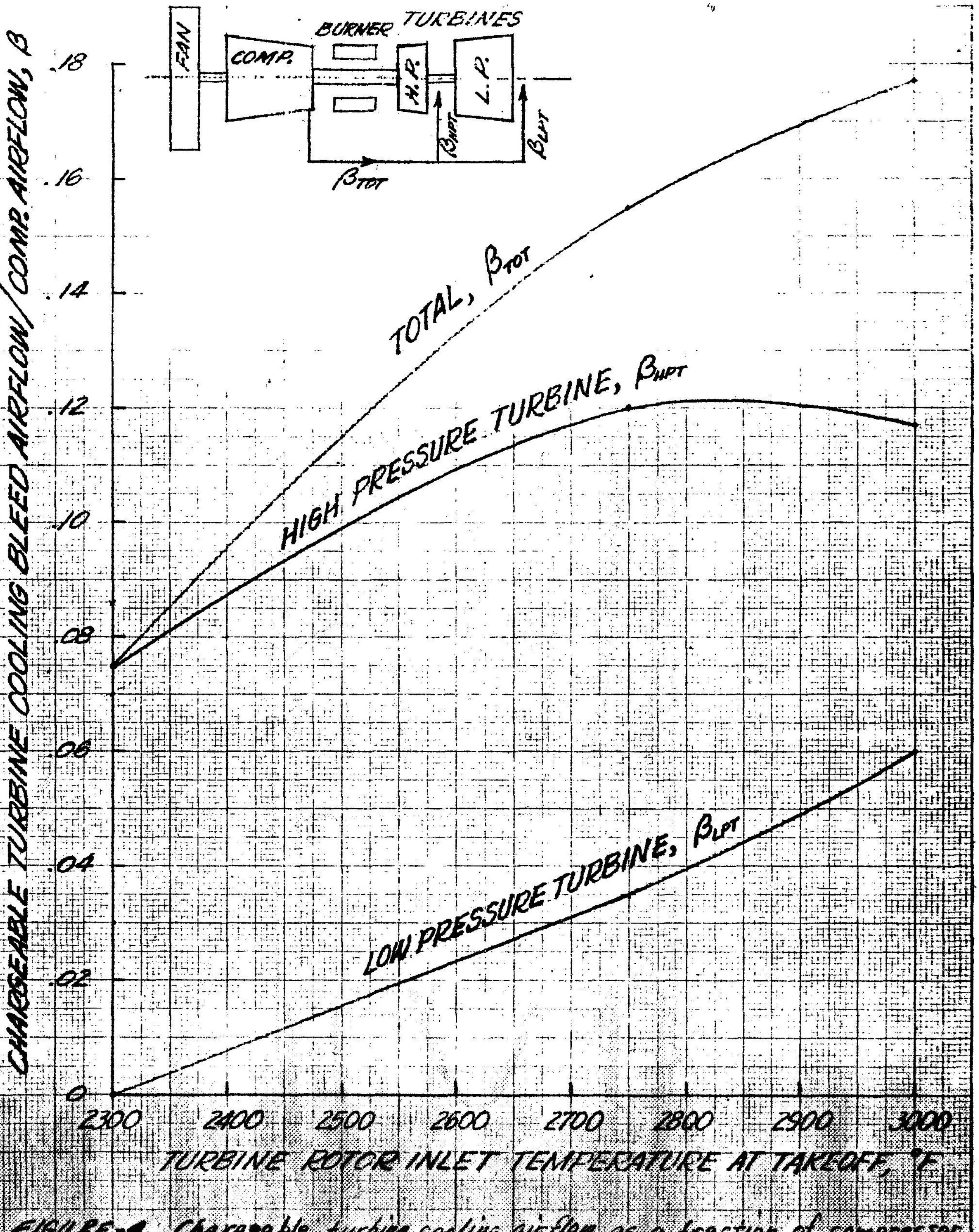


FIGURE-1. Chargeable turbine cooling airflow as a fraction of compressor airflow for various turbine-rotor-inlet-temperatures.

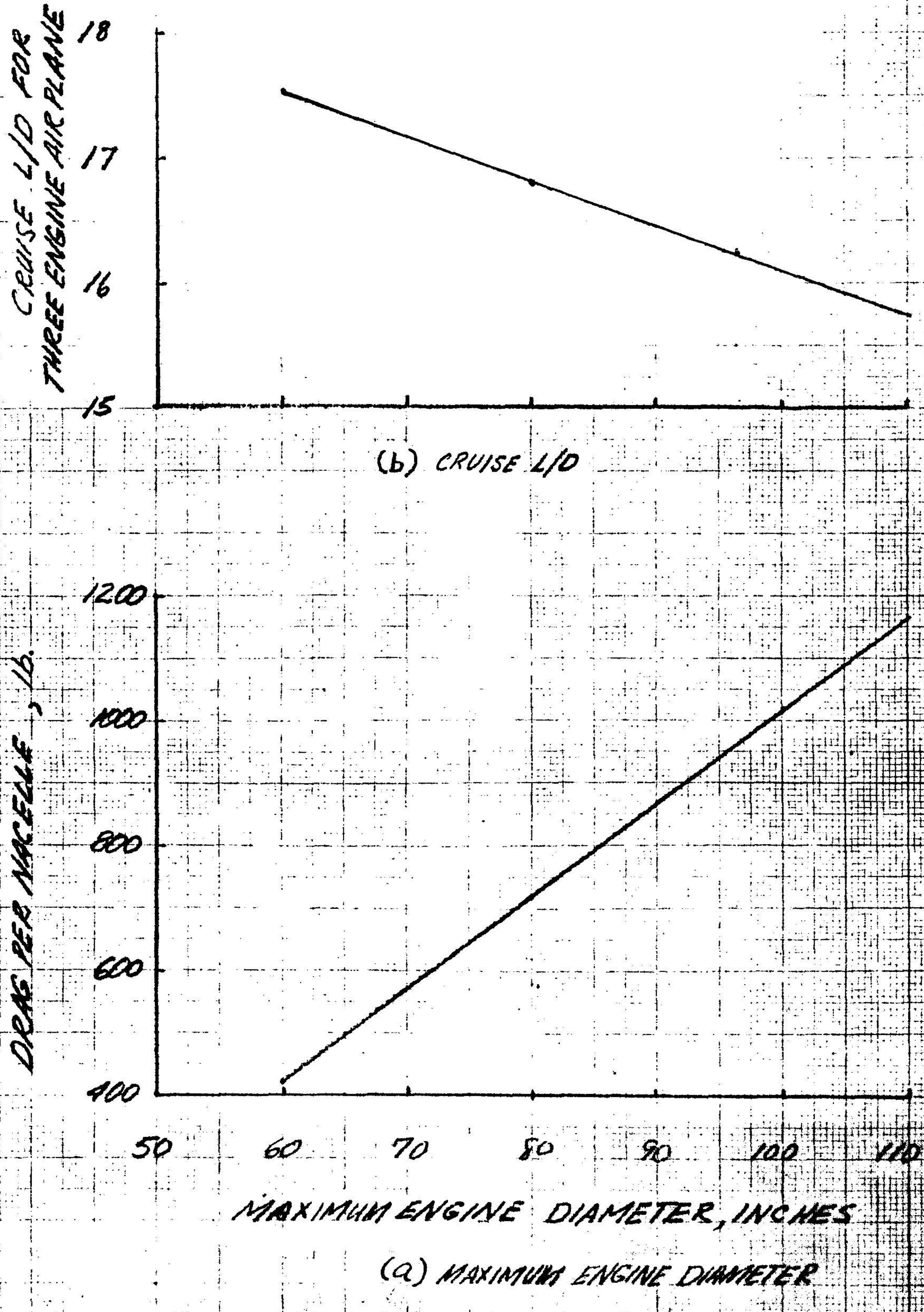


FIGURE 5.- Cruise L/D and engine nacelle drag versus maximum engine diameter.

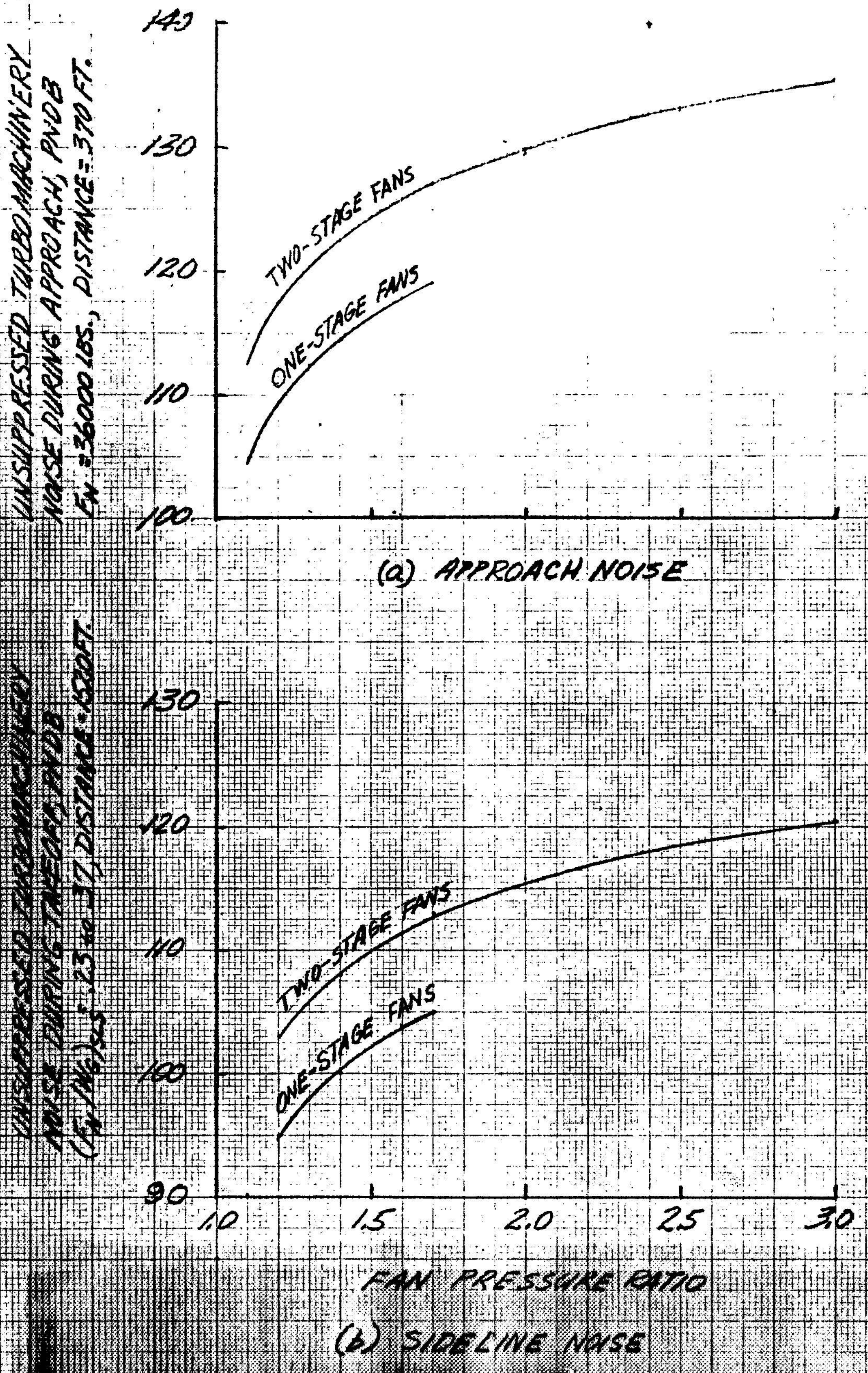


FIGURE 6.- Unsuppressed turbomachinery noise during approach and takeoff for one and two stage fan engines. Airplane TOGW = 386 000 lb. Noise numbers estimated to be within ± 2 PNDB.

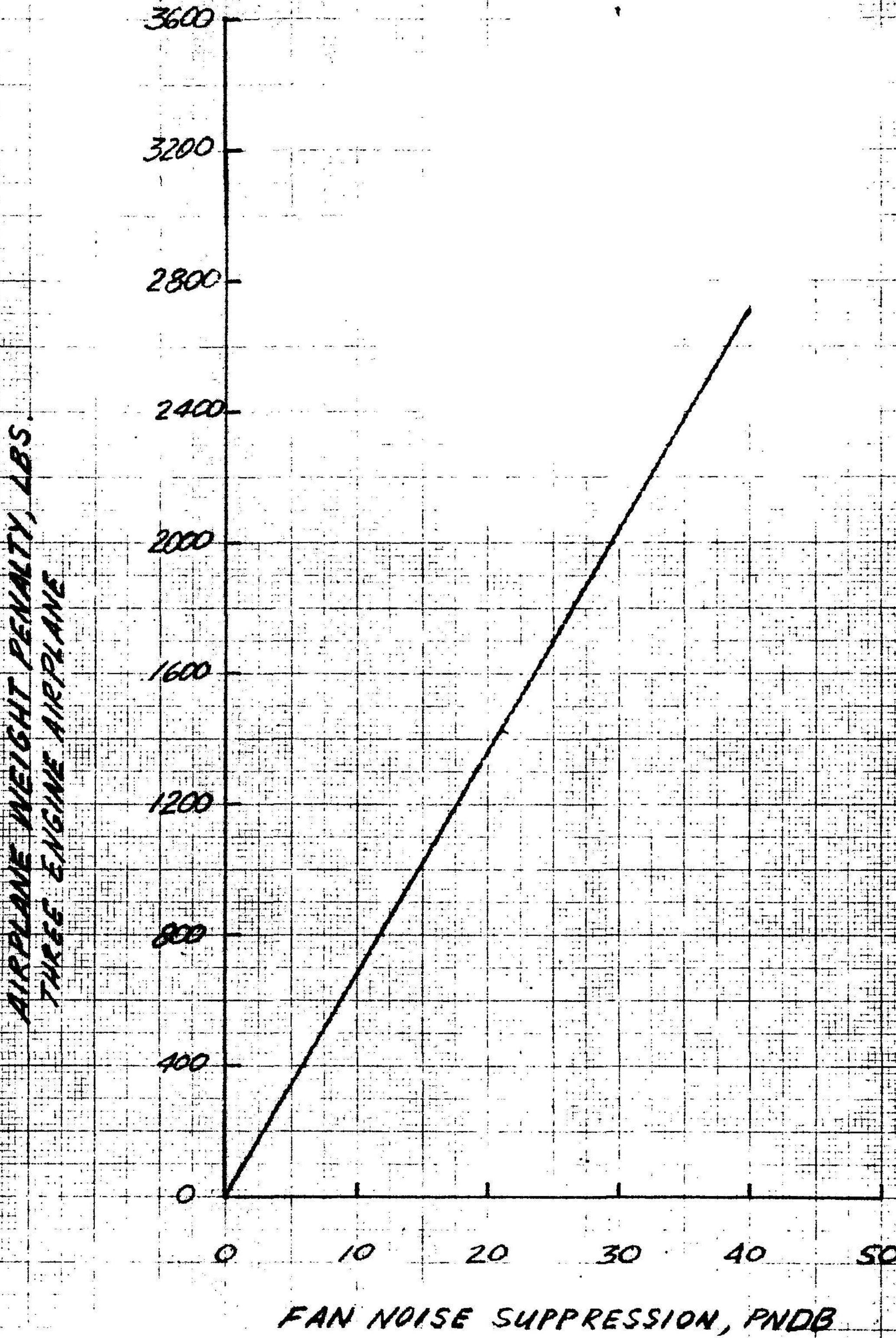


FIGURE 7.- Airplane weight penalty versus fan turbomachinery noise suppression needed. Weight is based on a three engine airplane with a maximum engine diameter of 80 inches.

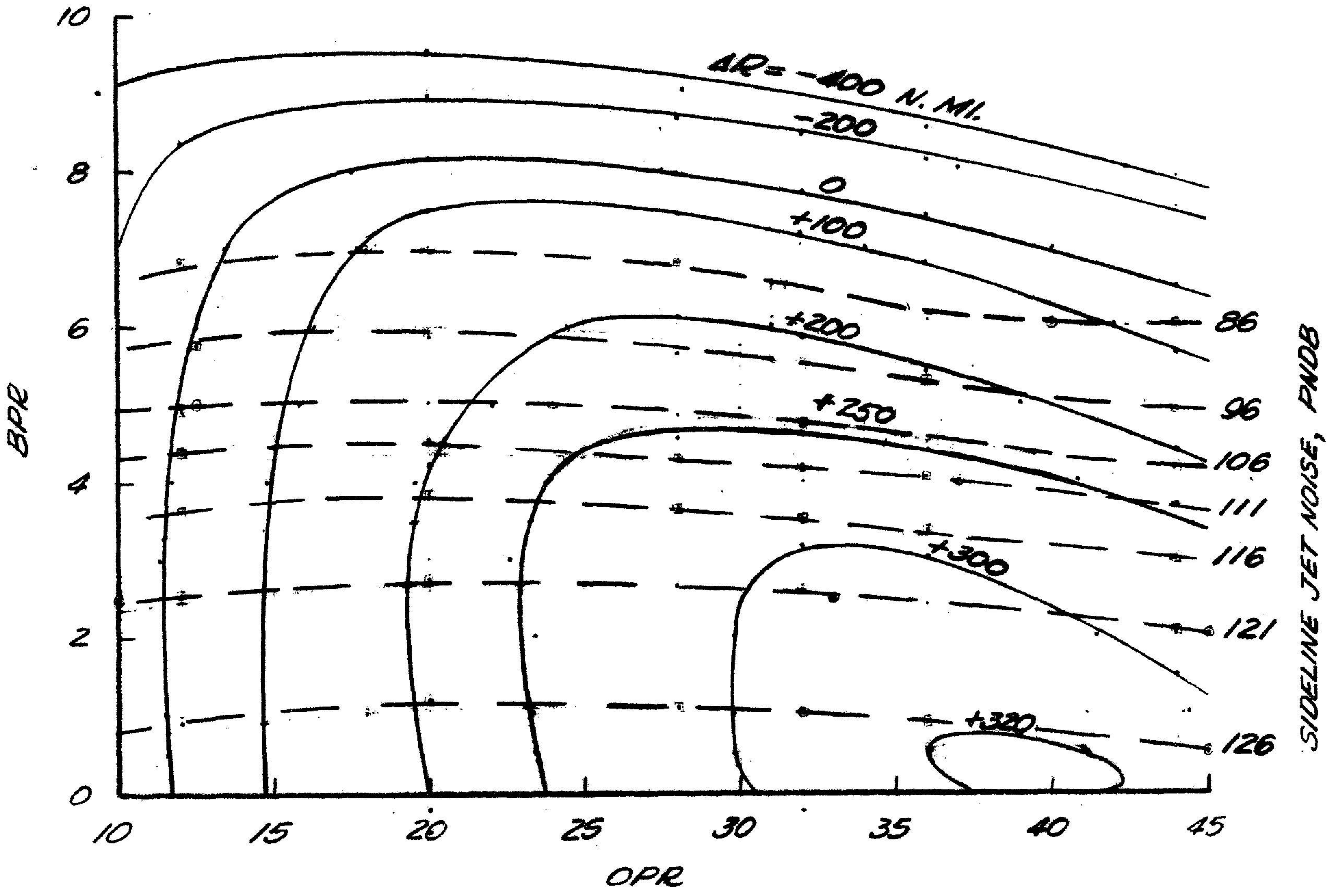


FIGURE 8.- Range contours and unsuppressed sideline jet noise levels versus bypass ratio and overall pressure ratio. Takeoff T_4 = 2300°F, cruise T_4 = 2100°F, R_{REF} = 3000 n. mi., cruise MN=0.98, β_{HPT} = 7.5%, β_{LPT} = 0%, L/D varies with engine diameter, jet noise by SAE method, FPR=1.70. Machinery noise suppression weight penalty is not included in the range calculation.

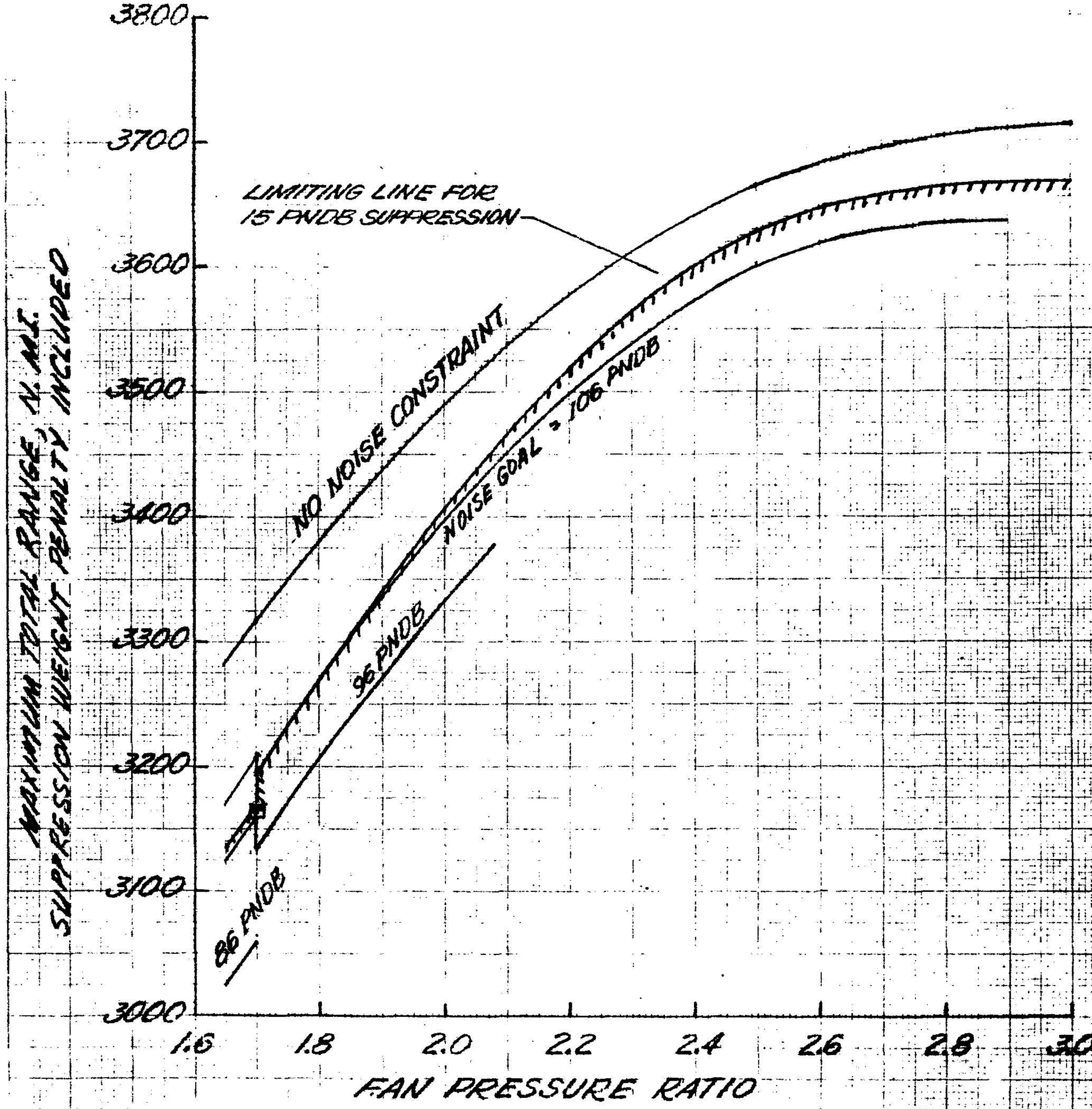


FIGURE 9.- Maximum total range versus fan pressure ratio for several noise goals. Suppression weight penalty included. Takeoff $T_4 = 2300°F$, cruise $T_4 = 2100°F$, MN=0.98, $\beta_{HPT} = 7.5\%$, $\beta_{LPT} = 0\%$, L/D varies with engine diameter.

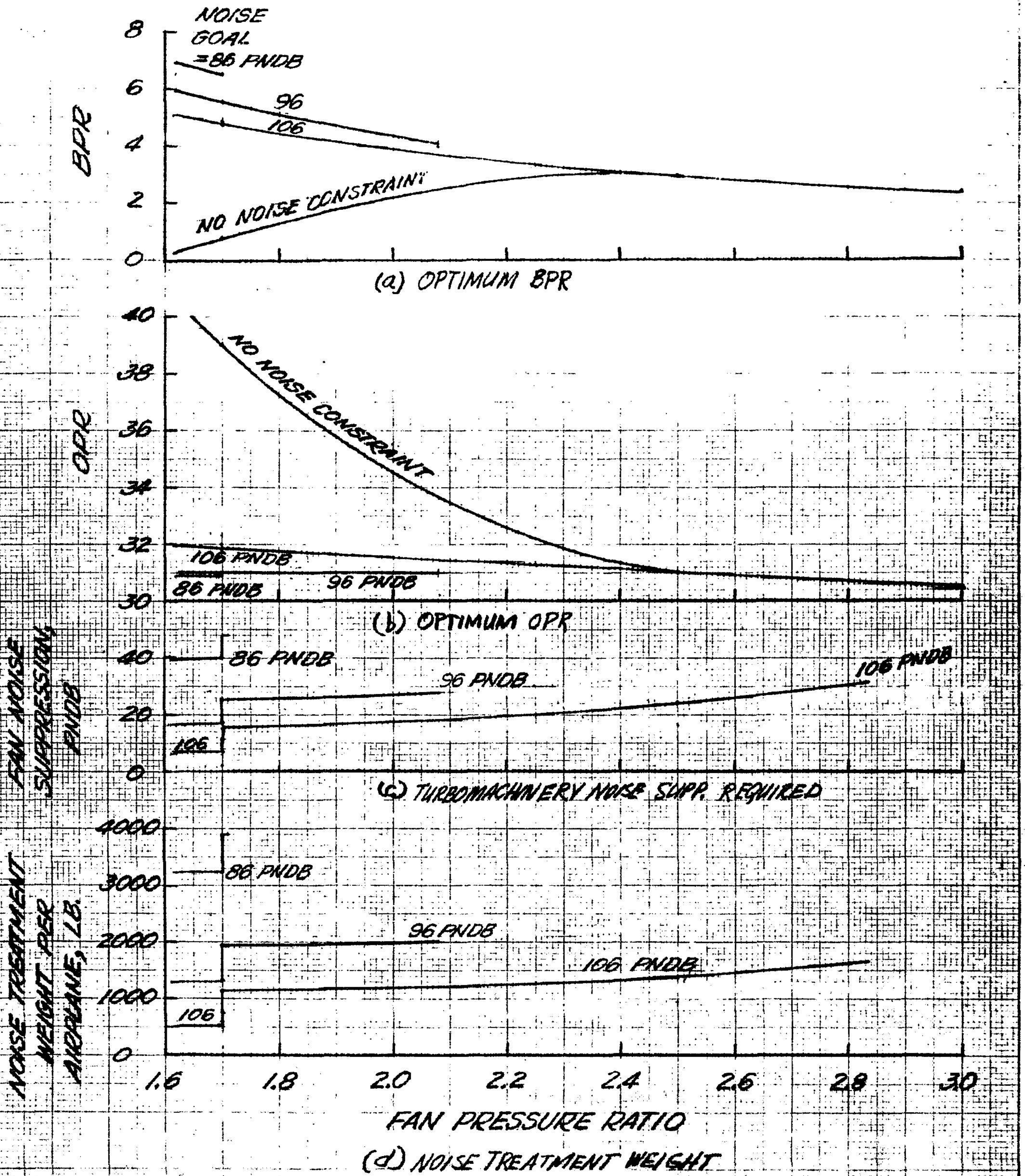


FIGURE 10.- Engine parameters versus fan pressure ratio. Takeoff $T_4 = 2300°F$, cruise $T_4 = 2100°F$, cruise MN=0.98, $\beta_{HPT} = 7.5\%$, $\beta_{LPT} = 0\%$, L/D varies with engine diameter

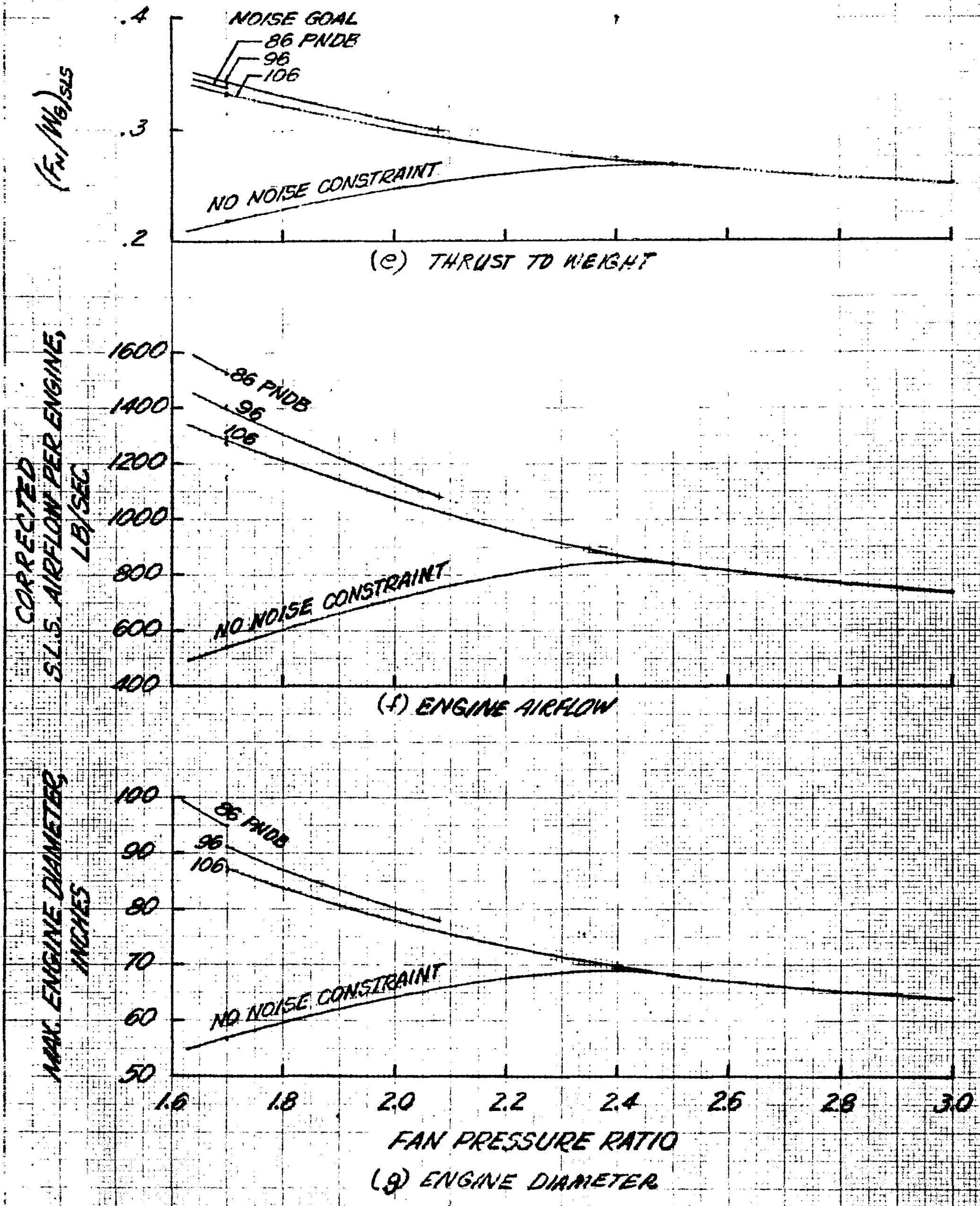


FIGURE 10.- Concluded.

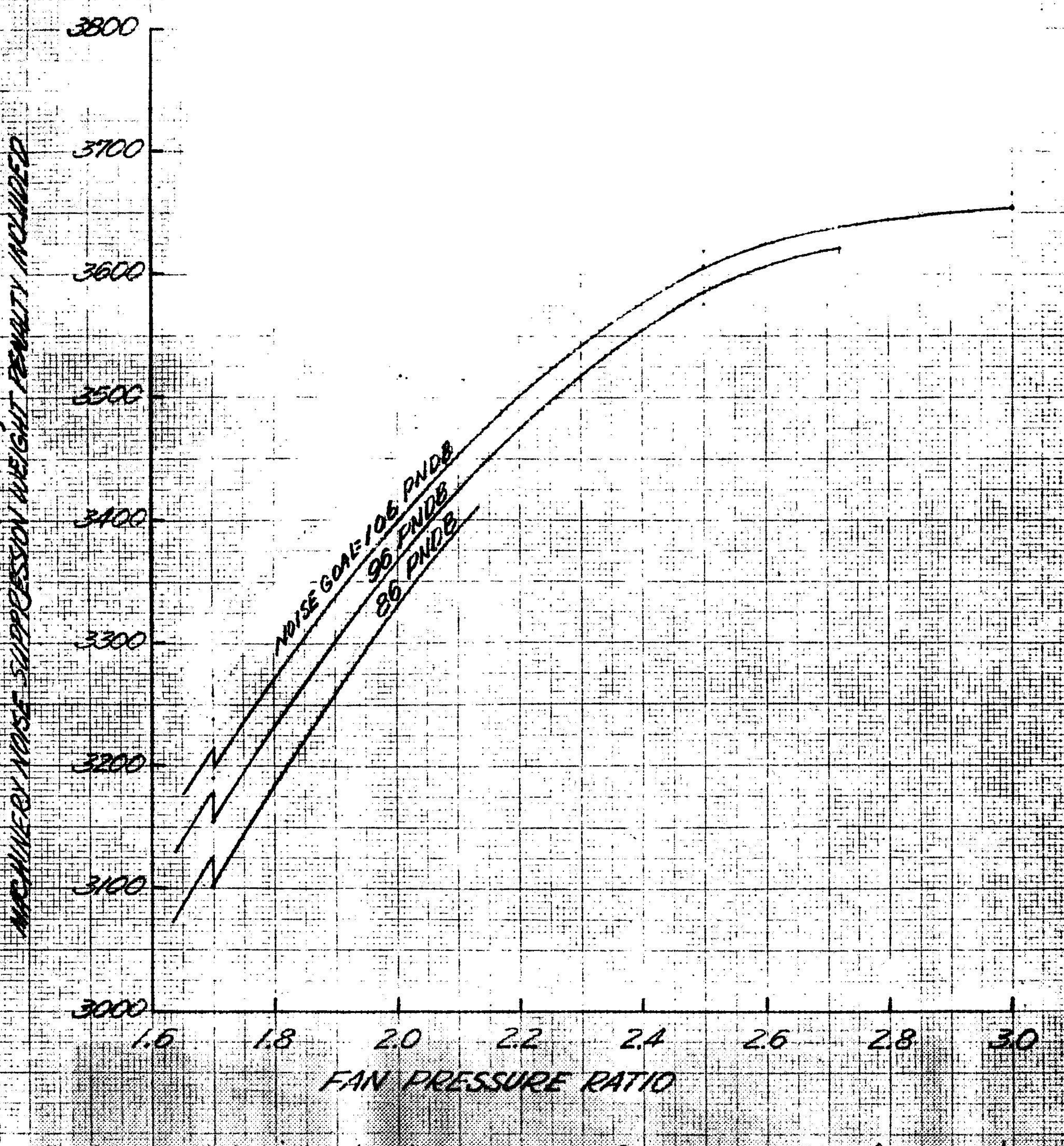


FIGURE 11.- Maximum total range versus fan pressure ratio for several noise goals. Takeoff T_4=2300°F, cruise T_4=2100°F, cruise MN=0.98, ΔP_{HT}=7.5%, ΔP_{CT}=0%, L/D varies with engine diameter, 10 PNdB jet noise suppressor assumed without weight penalty. Machinery noise suppression up to 40 PNdB assumed as necessary.

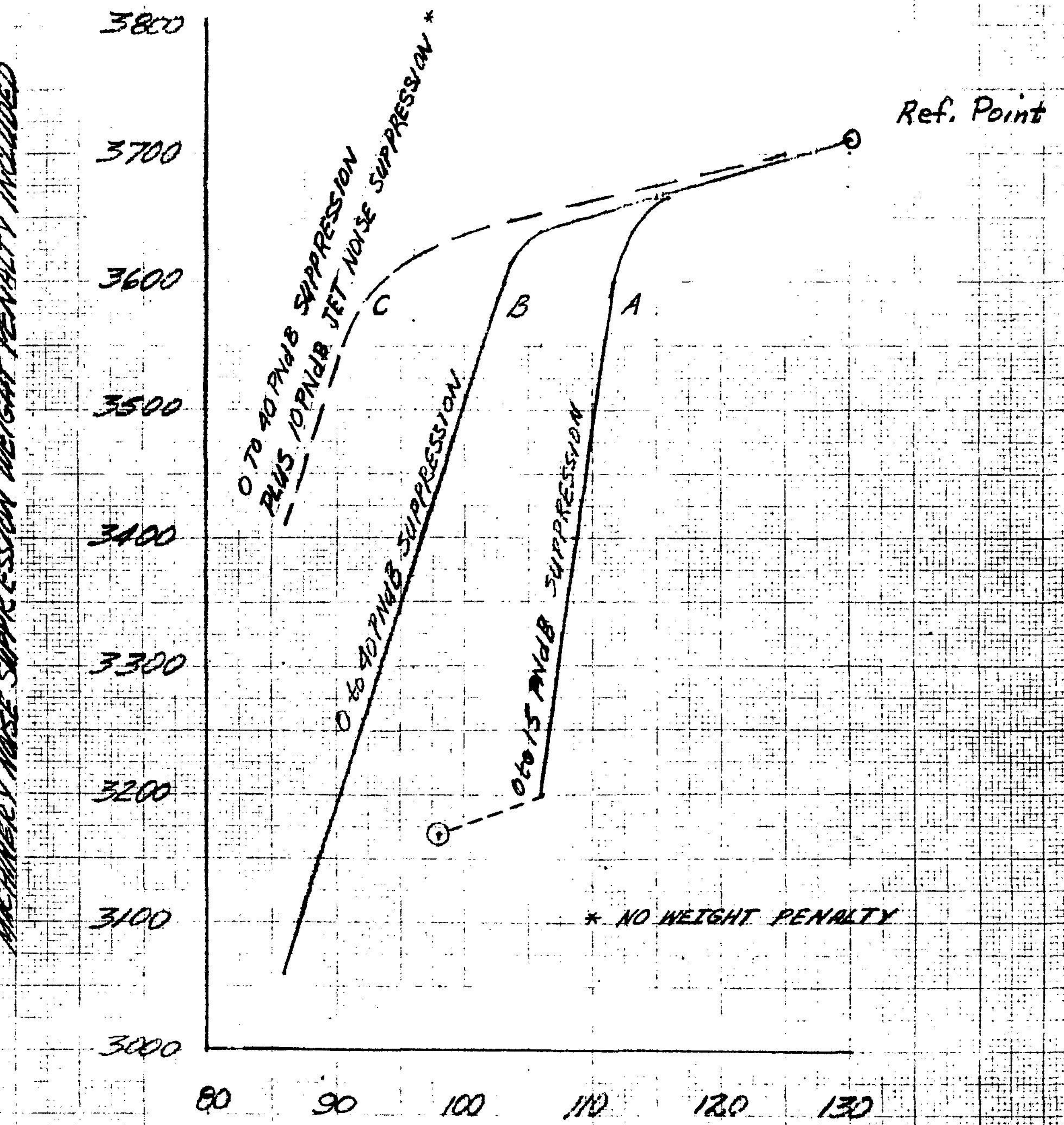


FIGURE 12.- Range versus noise tradeoff. Takeoff T_4=2300°F, cruise T_4=2100°F, Cruise MN=0.98, β_{HPT}= 7.5%, β_{LPT}=0%, L/D varies with engine diameter.

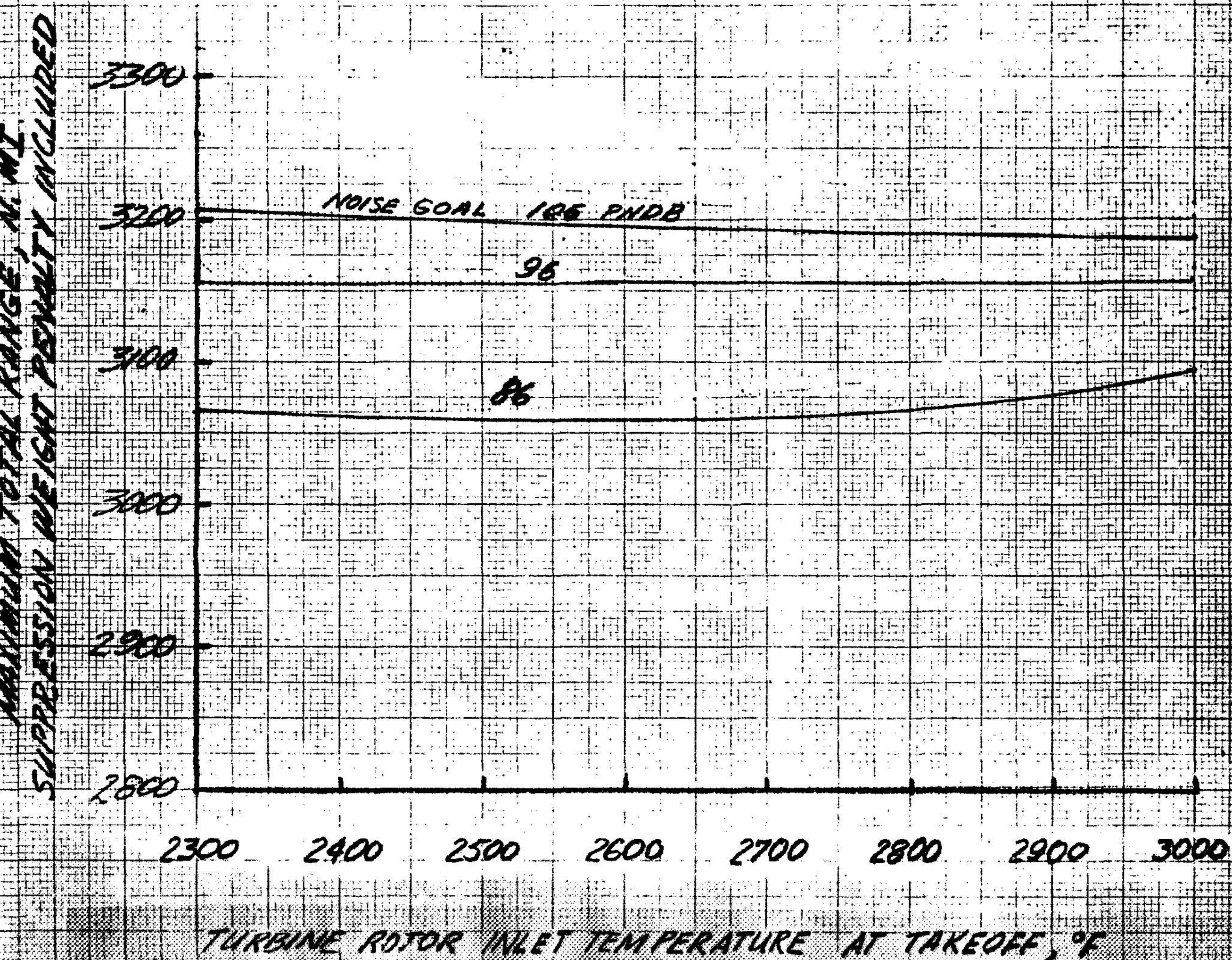


FIGURE 13.- Maximum total range versus turbine-rotor-inlet-temperature at three noise goals. Cruise T_4 = takeoff T_4 minus 200°F, FPR=1.7 (one stage fan), cruise MN=0.98, L/D varies with engine diameter.

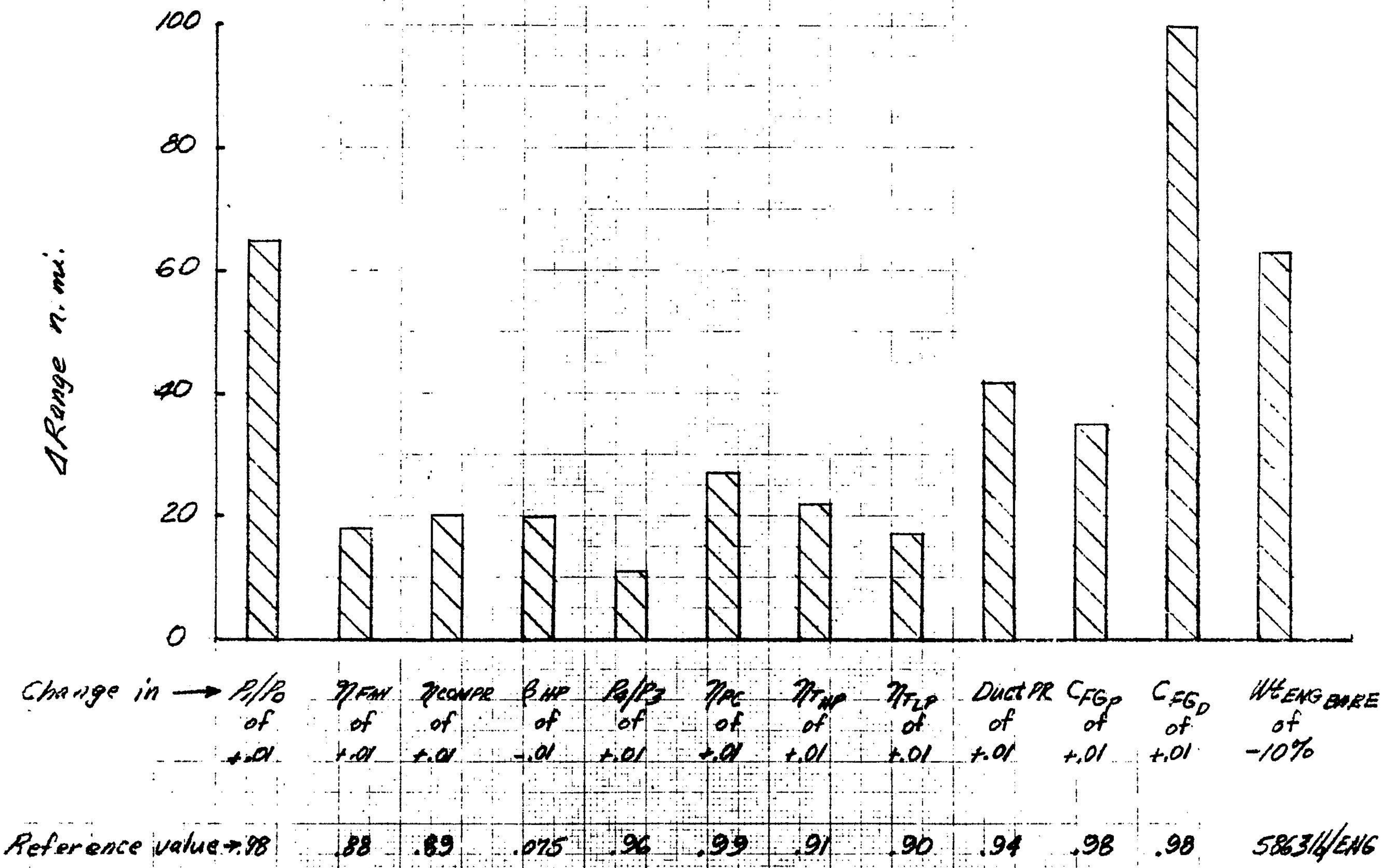


FIGURE 14.- Change in range for a change in engine design parameter. Reference engine, takeoff T_4 = 2,300°F, cruise T_4 = 2100°F, FPR = 1.70, OPR = 31.0, BPR = 4.8, cruise MN = 0.98.